

REMTECH inc.

Huntsville, Alabama



**SRB ENVIRONMENT  
EVALUATION AND ANALYSIS  
FINAL REPORT**

**VOLUME II: RSRB JOINT FILLING  
TEST/ANALYSIS IMPROVEMENTS**

**September 1991**

**Prepared by:**

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**Contract:**

**NAS8-37891**

**For:**

**Induced Environments Branch (ED33)  
National Aeronautics and Space Administration  
George C. Marshall Space Flight Center  
Marshall Space Flight Center, AL 35812**

## **FOREWORD**

This Technical Report documents the results of the analyses done on the redesigned Solid Rocket Booster (SRB) and the advanced SRB performed by REMTECH inc., under NASA/MSFC Contract NAS8-37891, Mr. L. D. Foster, ED33, CTOR. This report is presented in three volumes:

- Volume I:      Redesignated SRB Flight Heating Evaluation
- Volume II:     RSRB Joint Filling Test/Analysis Improvements
- Volume III:    ASRB Plume Induced Environment Studies

This Volume II documents the analyses and technical support provided the RSRB TPTA test program and improvements made to the analytical tools used in preparation for the ASRB TPTA test program. The duration of this support was from September 1989 through September 1991.

## ABSTRACT

Following the Challenger accident a very comprehensive solid rocket booster (SRB) redesign program was initiated. One objective of the program was to develop expertise at NASA/MSFC in the techniques for analyzing the flow of hot gases in the SRB joints. Several test programs were undertaken to provide a data base of joint performance with manufactured defects in the joints to allow hot gases to fill the joints. This data base was used also to develop the analytical techniques. Some of the test programs were Joint Environment Simulator (JES), Nozzle Joint Environment Simulator (NJES), Transient Pressure Test Article (TPTA), and Seventy-Pound Charge (SPC).

In 1988 the TPTA test hardware was moved from the Utah site to MSFC and several RSRM tests were scheduled, to be followed by tests for the ASRM program. REMTECH inc. supported these activities with pretest estimates of the flow conditions in the test joints, and post-test analysis and evaluation of the measurements. During this support REMTECH identified deficiencies in the gas-measurement instrumentation that existed in the TPTA hardware, made recommendations for its replacement, and identified improvements to the analytical tools used in the test support.

Only one test was completed under the TPTA RSRM test program, and those scheduled for the ASRM were rescheduled to a time after the expiration of this contract. The attention of this effort was directed toward improvements in the analytical techniques in preparation for when the ASRM program begins.

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## Section 1

# INTRODUCTION

Following the Challenger accident a very comprehensive solid rocket booster (SRB) redesign program was initiated. One objective of the program was to develop expertise at NASA/MSFC in the techniques for analyzing the flow of hot gases in the SRB joints. Several test programs were undertaken to provide a data base of joint performance with manufactured defects in the joints to allow hot gases to fill the joints. This data base was used also to develop the analytical techniques. Some of the test programs were JES, NJES, TPTA, and SPC.

In 1987 efforts were begun at MSFC to develop expertise in the analysis of hot gas flow in solid rocket motor joints. REMTECH inc. was contracted to support MSFC ED33 in these efforts. REMTECH selected the TOPAZ [1] code as the analytical tool to be used. The Seventy-Pound Charge (SPC) motor test program was used primarily as the data base with which to improve and verify the analytical techniques. Some analyses for the JES, NJES, TPTA, QM, and DM tests were performed as well. Late in this activity the motor segment unbond problem developed, and this technique had matured sufficiently to be a major help in evaluating the potential hazards of the unbonds, helping to preclude a major delay in the return-to-flight schedule for STS-26R. These activities are outlined in Ref. [2].

In 1988 the TPTA test hardware was moved from the Utah site to MSFC and several RSRM tests were scheduled, to be followed by tests for the ASRM program. As a follow-on to the prior support REMTECH inc. supported these activities with pretest estimates of the flow conditions in the test joints, post-test analysis and evaluation of the measurements for each test, and improvements in the analytical techniques used in the test analyses.

Only one test was completed under the TPTA RSRM test program and those scheduled for the ASRM were rescheduled to a time after the expiration of this contract. At this time the attention of this effort was directed toward improvements made in the analysis techniques in preparation for the ASRB TPTA test program.

This report documents the analyses and technical support provided by REMTECH to the RSRB TPTA test program and improvements made to the analytical tools used. The duration of this support was from September 1989 through September 1991.

## **Section 2**

### **SUPPORT ACTIVITY**

#### **2.1 RSRM TPTA Test 2.3**

This test was fired in August 1989, and a preliminary data review was held August 25, 1989. Included as Appendix 1 are the charts REMTECH presented at that meeting. It appeared that virtually all the gas pressure and temperature measurements were lost. In that briefing it was noted that 1) the loss of these data precluded analysis of the hot gas flow in the joints, and 2) the overall loss of these measurements, particularly temperature, seemed inordinately high. It was recommended that instrumentation installation techniques used in the SPC sub-scale tests be reviewed for possible application in these tests.

Subsequently, a TPTA 2.3 final data review meeting was held October 24, 1989, at which REMTECH presented an in-depth evaluation of the TPTA 2.3 measurements compared with both analysis and measurements from similar tests. The charts of that evaluation are included as Appendix 2. The conclusions of the preliminary review were unchanged. Included as Appendix 3 are the minutes of the final data review meeting in which REMTECH's recommendations were supported by Mr. Dallas Clark, ED64, and the proposal adopted for a series of meetings to review REMTECH's recommendations for TPTA instrumentation requirements and determine which can be implemented in the current test program.

#### **2.2 TPTA Instrumentation Requirements**

Based on post-test inspections of the TPTA 2.3 test hardware an urgent meeting was held with Mr. A. F. Domal, ED54, to review possible means of improving gas-measurement instrumentation quality for the next test (TPTA 1.4). A summary of the meeting is included as Appendix 4.

In response to a set of proposed TPTA 1.4 test requirements received from Sverdrup Technology (supporting ED54), REMTECH published a set of requirements [3] to meet the stated gas flow analysis objectives of the TPTA test program. That publication is included herewith as Appendix 5. In subsequent meetings of the TPTA test team (including Mr. B. F. Goldberg, Chief, ED54) it was concluded the needed revisions to the existing instrumentation in the TPTA hardware could not be made without additional resources. The matter was passed to RSRM Project Office for a decision whether to provide the additional funding or waive the requirements for the gas flow measurements. This action was taken through Mr. J. E. Hengel, ED33, and is documented in Appendix 6. The memoranda associated with this action elicited questions from Dr. J. C. Blair, Director, Structures and Dynamics Lab. REMTECH's response to these questions is documented in Appendix 7.

During this time the decision was given to cancel further TPTA testing until sometime in early 1994, when support for the ASRM would commence. This decision put continued support of this issue beyond the period of performance for this contract, so it was tabled until an appropriate later time when the ASRM test preparations begin.

## 2.3 Analysis Techniques Improvement

The one-dimensional (1-D) flow analysis code, TOPAZ, was selected to analyze the flow of hot gases in the field and nozzle/case joints of the RSRM. This code was developed at Sandia Laboratories for application to pipe flow in nuclear reactors and solar furnaces. The similarity of this type flow to that expected in the joints influenced the choice. Another reason for the choice is that TOPAZ solves the fully-coupled flow equations, whereas most other quick-look analysis techniques available at the time coupled at most two of the three equations. During the course of the SRM redesign analytical support, the code was modified to suit the needs of this application. The discussion that follows summarizes the major ones of those modifications.

In a joint analysis the motor pressure and temperature history are generally known as inputs. As initially received, TOPAZ required that these inputs be modeled using heat and mass generation schedules within the computational component that represents the bore conditions; this approach only approximated these input values and required several iterations to achieve adequate matching. REMTECH has added an option in the code that allows the input of the actual temperature and pressure directly. This change eliminates this iteration process and allows a more accurate representation of these boundary conditions.

REMTECH improved the mechanism for heat removal from the gas by adding an explicit solution for wall temperature of a 1-D semi-infinite slab as representative of a boundary surface in the joint. Previously TOPAZ based the convective heat transfer coefficient on a constant wall temperature. Also, an option has been added that models an ablating surface by fixing its wall temperature as the ablation temperature of the surface material if the variable temperature computed by the slab solution exceeds the ablation temperature. This feature models more accurately the removal of heat from the gas under ablating conditions.

REMTECH modified TOPAZ to compute the pipe friction factor and heat transfer to the wall based on the surface area of a non-circular cross-section conduit. Previously these non-circular geometries could only be approximated by the use of a hydraulic diameter. Roughness effects were added in the computation of the convective heat transfer. Also, increased heat transfer to a wall due to pipe entrance effects is now modeled in TOPAZ as well.

There are 23 different properties (pressure, temperature, mass flow, velocity, etc.) that are computed at each time point for each element in the flow model. Only a fixed 15 of these 23 could be accessed for print-out. Moreover, only 6 of these 15 could be printed out in a given run for all elements. This represented a severe limitation to the efficient use of the code and necessitated numerous repeat runs to get all the needed



information. Now all 23 properties can be accessed and a total of 100 values can be printed out for each run.

The on-line TOPAZ User's Guide has been updated to reflect all of these changes. Detailed documentation of these changes is contained in a REMTECH Technical Note included herewith as Appendix 8.

## Section 3

### SUMMARY/RECOMMENDATIONS

Based on the accomplishments under this contract the following summary and recommendations are made:

1. A quick-analysis 1-D CFD code has been developed for application to hot gas flow in the joints of solid rocket boosters and verified by comparisons with hot motor firing data bases. Several improvements were made to the code making it more suitable to this application. This code contributes to the maintenance of expertise in solid rocket motor performance analysis at NASA/MSFC.
2. The gas flow instrumentation in the TPTA test hardware experienced a high mortality rate such that, by the time the hardware was transferred to MSFC, the available instrumentation was sufficiently reduced so as to render it inadequate to support an analysis of motor joint performance. In most cases the instrumentation that survived gave suspect measurements and/or was located inauspiciously.
3. The difficulties with the gas flow instrumentation on the RSRM TPTA test hardware were built into the program from the design phase, i.e., the instrumentation selection and installation design. Once in place it proved too difficult to replace a faulty design. Hopefully, this documentation of the disappointing results from the RSRM TPTA test program will obviate the recommendation that any gas flow instrumentation to be installed in the ASRM TPTA hardware be scrutinized by the most experienced people available and reviewed by as wide as possible a peer review. Also, within reasonable cost constraints, critical measurements should have both redundant instrumentation as well as cabling. This emphasis should be introduced into the pretest planning and preparation for the ASRM TPTA test program ASAP.

## Section 4

### REFERENCES

- [1] Winters, W. S., "TOPAZ — A Computer Code for Modeling Heat Transfer and Fluid Flow in Arbitrary Networks of Pipes, Flow Branches, and Vessels," Sandia Report SAND83-8253, Sandia National Laboratories, Livermore, California, Jan. 1984.
- [2] Crain, W. K., Knox, E. C., Frost, C. L., and Engel, C. D., "Final Report, SRB Thermal Environments," REMTECH Technical Report, RTR 142-03, June 1989.
- [3] Woods, Hamilton, "TPTA 1.4 Instrumentation Requirements," REMTECH Memorandum, RM 213-01, April 1990.

## **Appendix 1**

### **TPTA 2.3 PRELIMINARY DATA REVIEW**



REVIEW OF GAS PRESSURES  
AND TEMPERATURES IN FIELD  
AND NOZZLE/CASE JOINTS  
OF TPTA 2.3 MOTOR TEST FIRING

E. C. Knox  
G. H. Woods

August 25, 1989



# FIELD JOINT A



## • Instrumentation Needed for Joint Filling Analysis

INSTRUMENT	LOCATION	DATA AVAILABLE
P034	21° Slot Pressure	Lost
P035	147° Slot Pressure	O.K.
P036	261° Slot Pressure	O.K.
P078	341° Capture Feature Seal Pressure	Lost
P133	218° Capture Feature Seal Pressure	Lost
P120	223° Primary Seal Pressure	Capture Feature Sealed
T162	135° Capture Feature Gas Temperature	Lost
T164	341° Capture Feature Gas Temperature	Lost
T214	223° Capture Feature Gas Temperature	Lost
T228	223° Capture Feature Gas Temperature	Lost

## FIELD JOINT B



- Instrumentation Needed for Joint Filling Analysis

INSTRUMENT	LOCATION	DATA AVAILABLE
	Slot Pressures	O.K.
P123	228° Capture Feature Seal Pressure	158 psi peak
T184	111° Slot Temperature	4000 °F peak
T185	291° Slot Temperature	2500 °F peak
T165	135° Capture Feature Gas Temperature	Lost
T167	341° Capture Feature Gas Temperature	Lost
T085	135° Primary Gas Temperature	Lost
T086	341° Primary Gas Temperature	Lost

# NOZZLE/CASE JOINT D



- Instrumentation Needed for Joint Filling Analysis

INSTRUMENT	LOCATION	DATA AVAILABLE
P055	76° Primary Seal Pressure	O.K.
P056	166° Primary Seal Pressure	O.K.
P059	68° Inter-O-Ring Pressure	Primary Seal Held
P060	166° Inter-O-Ring Pressure	O.K.
P062	338° Inter-O-Ring Pressure	O.K.
T135	76° Primary Gas Temperature	Lost
T136	166° Primary Gas Temperature	Lost
T137	256° Primary Gas Temperature	Lost
T138	346° Primary Gas Temperature	Lost



- CONCLUSIONS

- Loss of data in crucial locations prohibits analysis of combustion flow in test joints.
- Pressures behind capture feature in joints A and B and behind primary in joint D indicate that no O-rings failed during motor operation.

- OBSERVATIONS

- Overall loss of measurements, particularly temperature, seemed inordinately high.
- It appeared that when one temperature in a region was lost, all like measurements were lost. This suggests common path hook-up and failure in the path, instead of in the transducers. On future tests the independence of measurement paths for like measurements should be maximized.
- Review of instrumentation installation techniques used in 70 pound motor tests may be helpful.
- If high transducer mortality cannot be avoided, more redundancy in crucial measurements is needed.

## **Appendix 2**

### **TPTA 2.3 FINAL DATA REVIEW**



# **TPTA 2.3 FINAL DATA REVIEW PRESSURES AND TEMPERATURES**

by  
Hamilton Woods  
REMTECH, Inc., Huntsville, AL  
in support of Dave Bacchus, ED 33

*October 24, 1989*

## TPTA 2.3 FINAL DATA REVIEW



- ☐ ***Test Objectives***
- ☐ ***System Performance***
- ☐ ***Quality of Test Data***
- ☐ ***Comparison with Previous Test Results***
- ☐ ***Comparison with Analytical Results***
- ☐ ***Adequacy of Test Data***

## TPTA 2.3 FINAL DATA REVIEW



### ***Test Objectives***

Provide additional test data which can be used to increase the reliability of the data used to verify the sealing capability of RSRM joints.

- ☐ Demonstrate the ability of the nozzle-to-case joint seal system, in a fail-safe mode with pressure to the primary O-ring to provide a pressure seal and accomodate structural deflections during the ignition pressure transient.
- ☐ Demonstrate that the field and nozzle-to-case joint insulation maintains structural integrity during assembly except as a result of any intentional insulation / case unbonds.
- ☐ Establish SRM joint performance historical data base and provide data for analytical model validation.

## TPTA 2.3 FINAL DATA REVIEW



### ***System Performance***

- ☐ Field joint A capture feature O-ring was eroded but maintained pressure seal.
- ☐ Nozzle / case joint D primary O-ring maintained pressure seal.
- ☐ Joint inspection suggests that polysulfide extruded through intentional flaw in nozzle / case wiper O-ring, restricting flow through flaw.
- ☐ No heat-effect observed on either wiper or primary O-ring in nozzle / case joint.
- ☐ Instrumentation in test joints did not supply enough information to establish SRM joint performance historical data base or to provide data for analytical model validation.

# TPTA 2.3 FINAL DATA REVIEW



## ***Quality of Test Data***

### 45 PRESSURE TRANSDUCERS

Questionable or Bad Pressure Measurements

MSID	JOINT	DEG	LOCATION	FAILURE
P78	A	341	Capture Feature	Bad/WYLE
P133	A	218	Capture Feature	Bad/WYLE

### 70 THERMOCOUPLES

Questionable or Bad Temperature Measurements

MSID	JOINT	DEG	LOCATION	FAILURE
T135	D	75.6	Primary	70°F Const
T136	D	165.6	Primary	70°F Const
T137	D	255.6	Primary	70°F Const
T138	D	345.6	Primary	70°F Const
T162	A	135	Capture Feature	34°F Const
T164	A	341	Capture Feature	Bad/WYLE
T 214	A	223	Capture Feature	Bad/WYLE
T228	A	223	Capture Feature	Bad/WYLE
T229	B	223	Capture Feature	Bad/WYLE



## TPTA 2.3 FINAL DATA REVIEW



### ***Comparison with Previous Test Results - JES-3B***

#### Joint A (Field Joint)

- ☐ Test flaw geometry

Insulation flaw: 0.125"x0.05"

Same as for JES-3B

- ☐ Head end pressures

Pressure History at head end was essentially same  
for TPTA 2.3 and JES-3B

- ☐ Capture feature pressure traces

Measurements for TPTA 2.3 bad

Only one measurement available from JES-3B

- ☐ Capture feature temperature traces

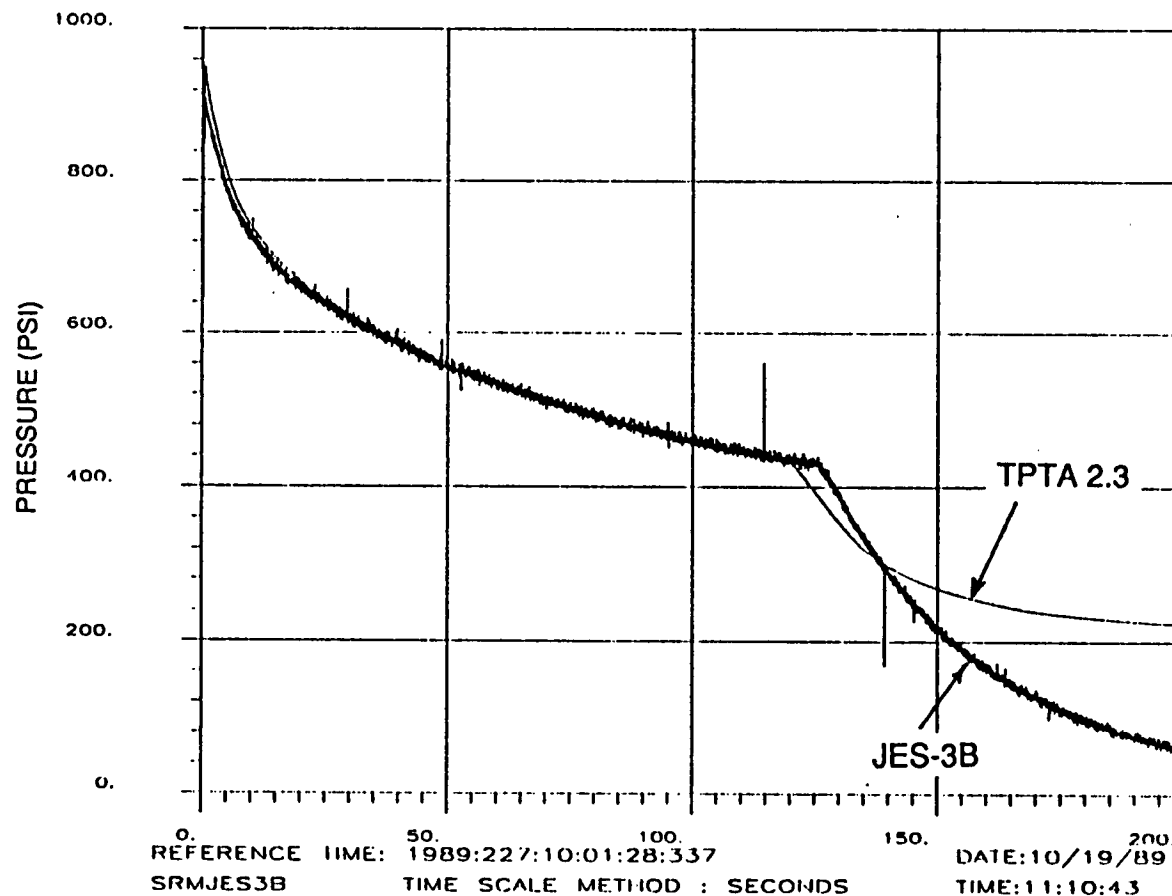
Measurements for TPTA 2.3 bad

Only one measurement available from JES-3B

# TPTA 2.3 FINAL DATA REVIEW



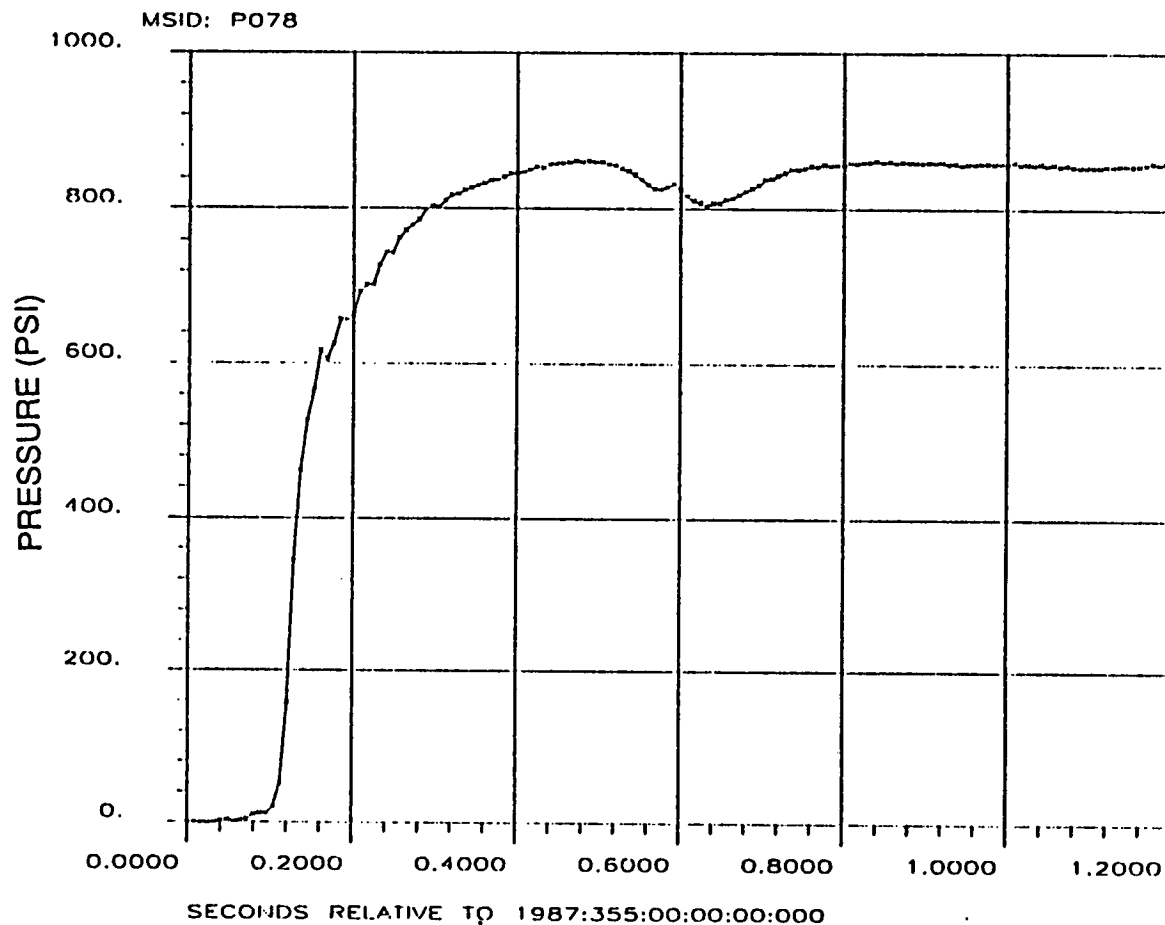
## Comparison of Bore Pressure Histories for TPTA 2.3 and JES-3B



# TPTA 2.3 FINAL DATA REVIEW



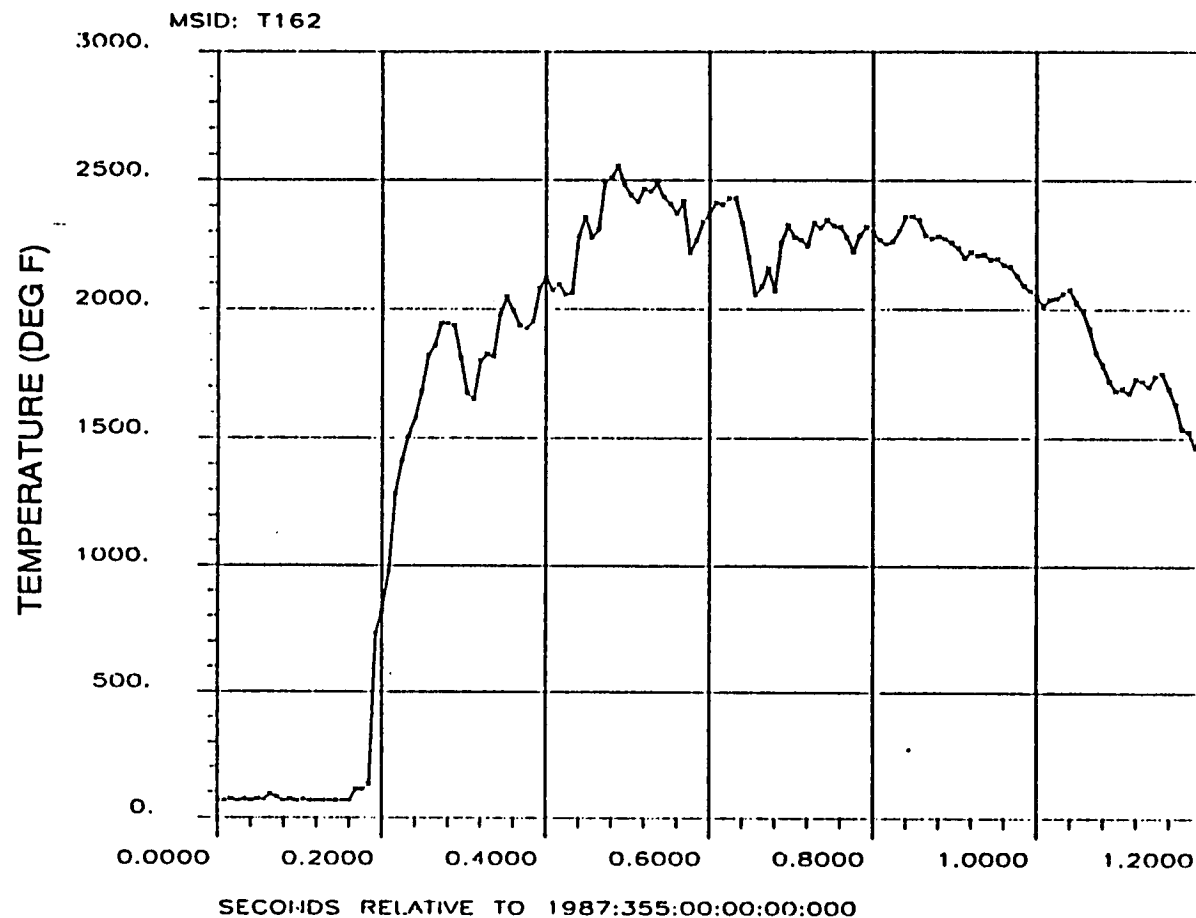
## Capture Feature Seal Pressure 90° from Flaw for JES-3B Field Joint A



## TPTA 2.3 FINAL DATA REVIEW



### Capture Feature Seal Temperature 90° from Flaw for JES-3B Field Joint A



## TPTA 2.3 FINAL DATA REVIEW



### ***Comparison with Previous Test Results-TPTA 2.1***

Joint B (Field Joint)

☐ Test geometry

Intentional J-SEAL adhesive insulation unbond

No similar tests performed - Compared with pristine field joint

☐ Capture feature pressure traces

MSID	DEG	MAXIMUM PRESSURE (PSI)	
		TPTA 2.3	TPTA 2.1
P079	135	465	N/A
P081	341	62	78.4
P123	228	158	191.3

☐ Capture feature temperature traces

MSID	DEG	TEMPERATURE MAXIMUM PRESSURE (°F)	
		TPTA 2.3	TPTA 2.1
T165	135	33	33
T167	341	32.4	33
T215	223	32.8	58.5



## TPTA 2.3 FINAL DATA REVIEW



### ***Comparison with Previous Test Results - TPTA 1.2***

Joint D (Nozzle/Case Joint)

☐ Test Flaw Geometry

TPTA 2.3: 0.35" Wide Polysulfide Defect, 1" Wiper O-Ring Flaw

TPTA 1.2: 0.25" Wide Polysulfide Defect, 1" Wiper O-Ring Flaw

☐ Head end pressures

Pressure history at head end was essentially same for TPTA 2.3 and TPTA 1.2

☐ Primary pressure traces

At flaw:  $P_{MAX} = 630$  psi for TPTA 2.3

$= 880$  psi for TPTA 1.2

90° from flaw: TPTA 2.3 joint D data did not exhibit flow symmetry

☐ Primary temperature traces

At flaw:  $T_{MAX} = 70^{\circ}$  F for TPTA 2.3

$T_{MAX} = 550^{\circ}$  F for TPTA 1.2

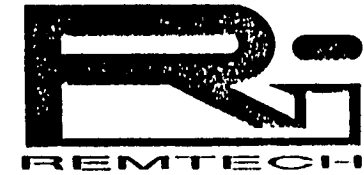
90° from flaw:  $T_{MAX} - T_{INIT} = 0^{\circ}$  F for TPTA 2.3

$T_{MAX} - T_{INIT} = 6^{\circ}$  F for TPTA 1.2

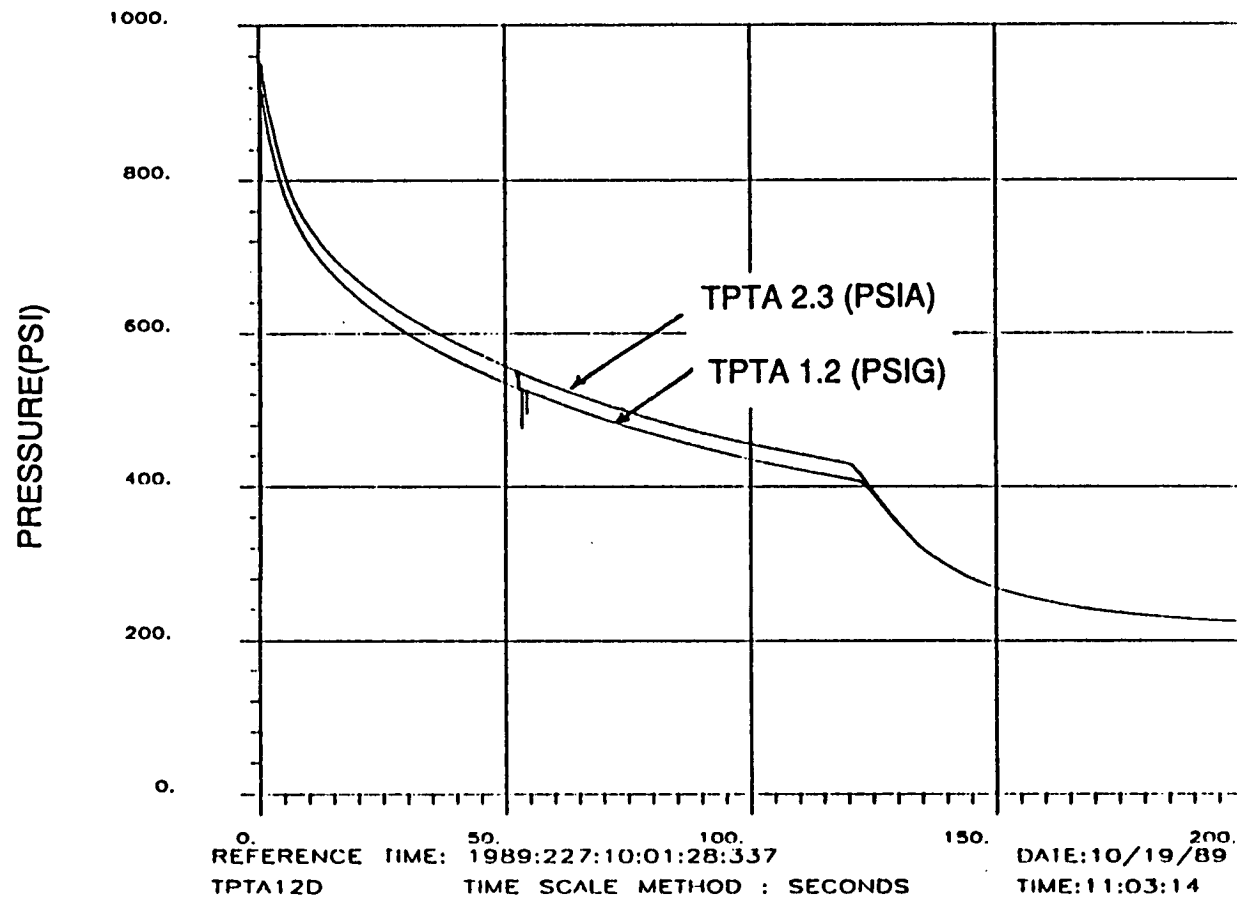
Joints C, E, F, and G (Non-test Joints)

Transducers measured ambient conditions

# TPTA 2.3 FINAL DATA REVIEW



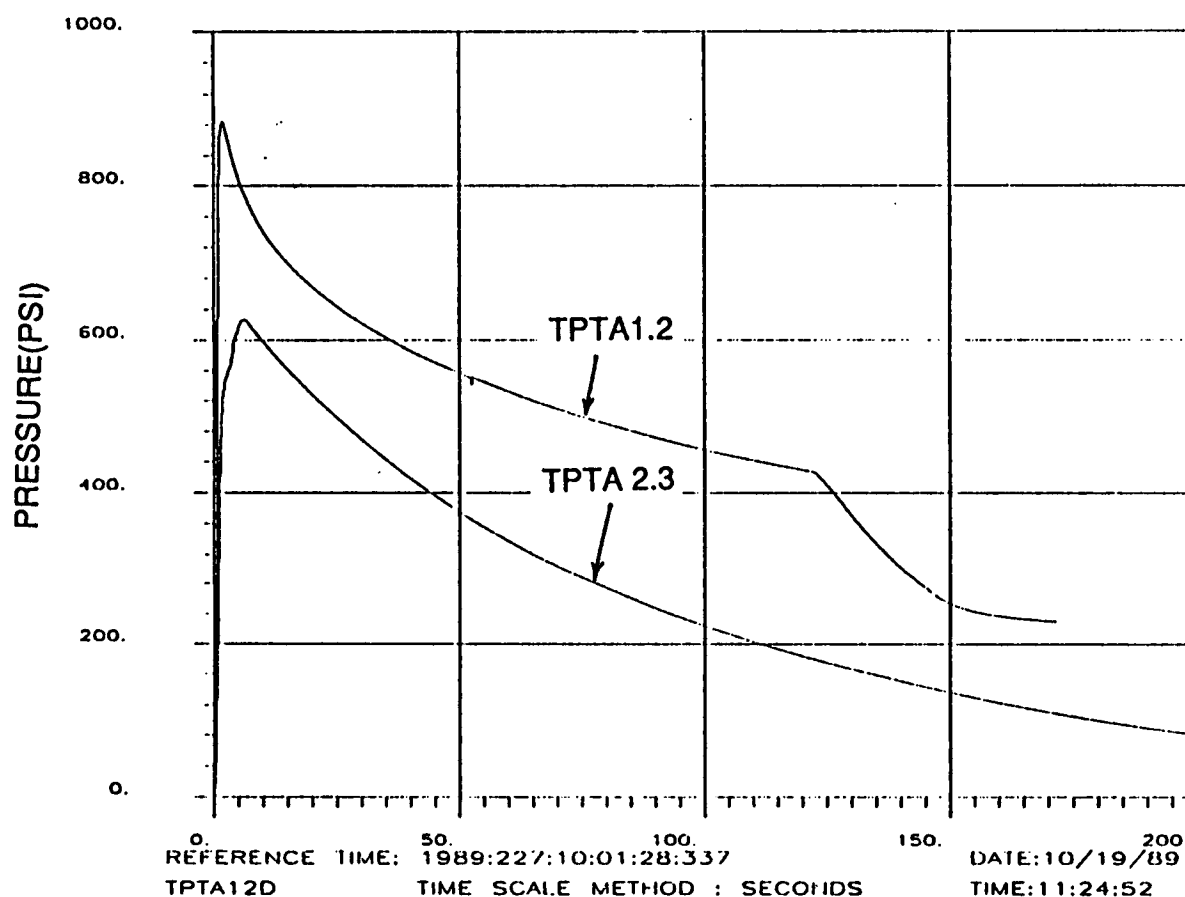
## Comparison of Bore Pressure Histories for TPTA 2.3 and TPTA 1.2



## TPTA 2.3 FINAL DATA REVIEW



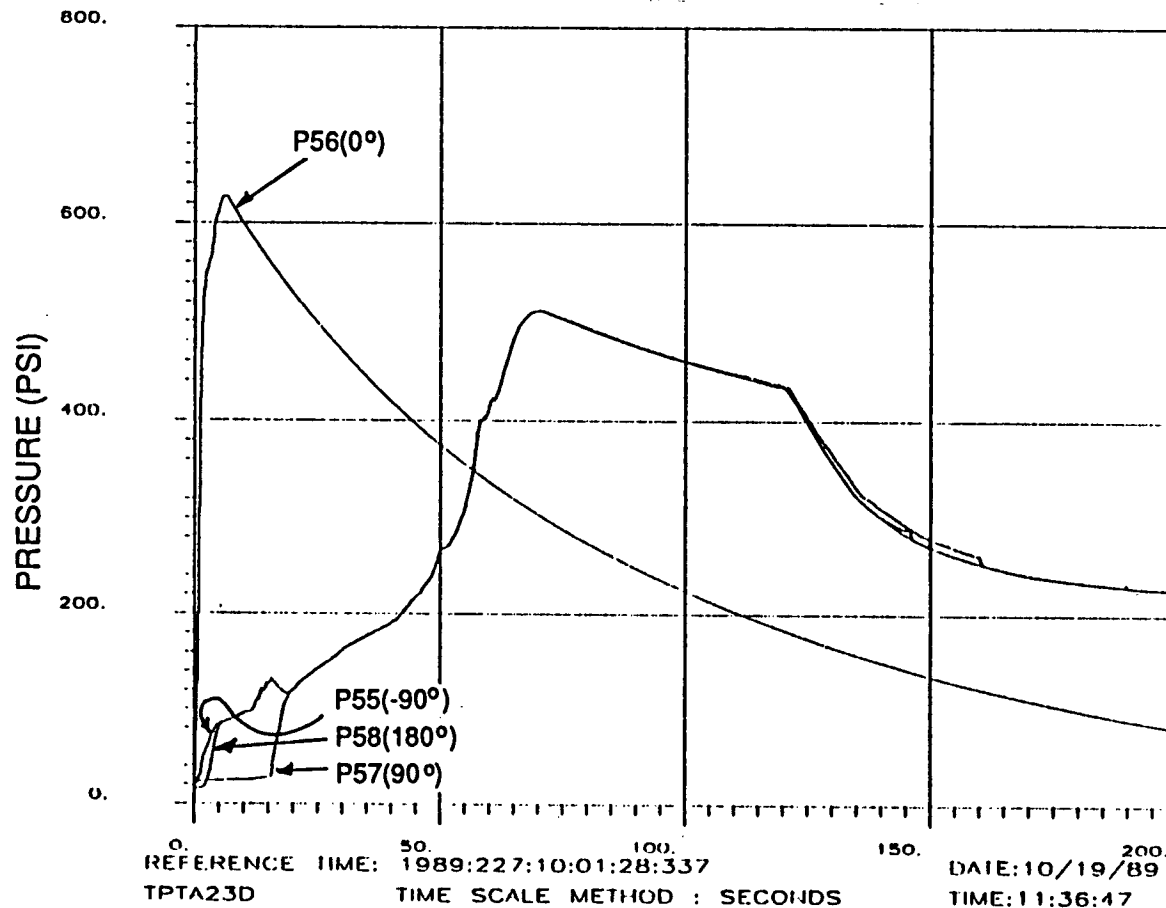
Comparison of Primary Seal Pressures at Flaw  
for TPTA 2.3 and TPTA 1.2 Nozzle/Case Joints



# TPTA 2.3 FINAL DATA REVIEW



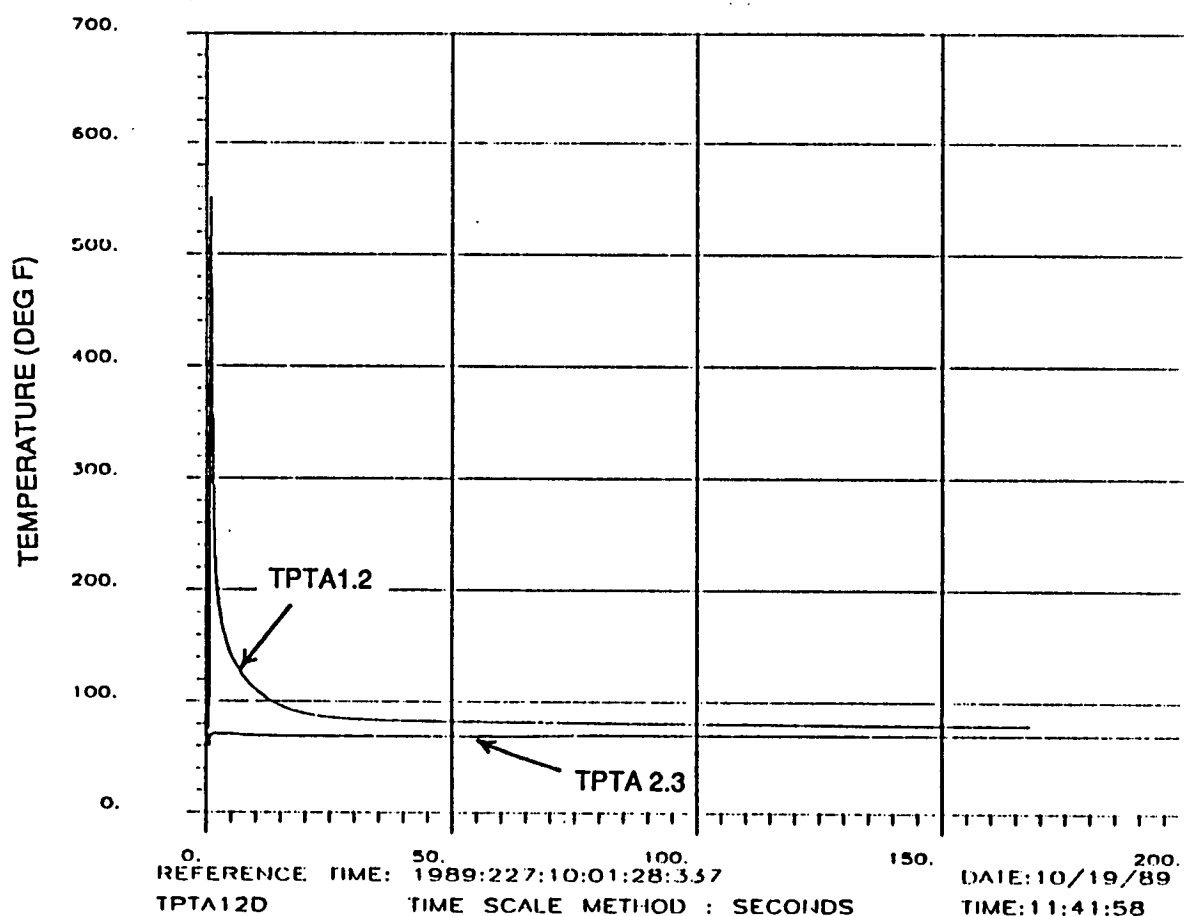
## Circumferential Primary Seal Pressure Distribution for TPTA 2.3 Nozzle/Case Joint



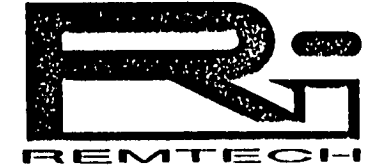
## TPTA 2.3 FINAL DATA REVIEW



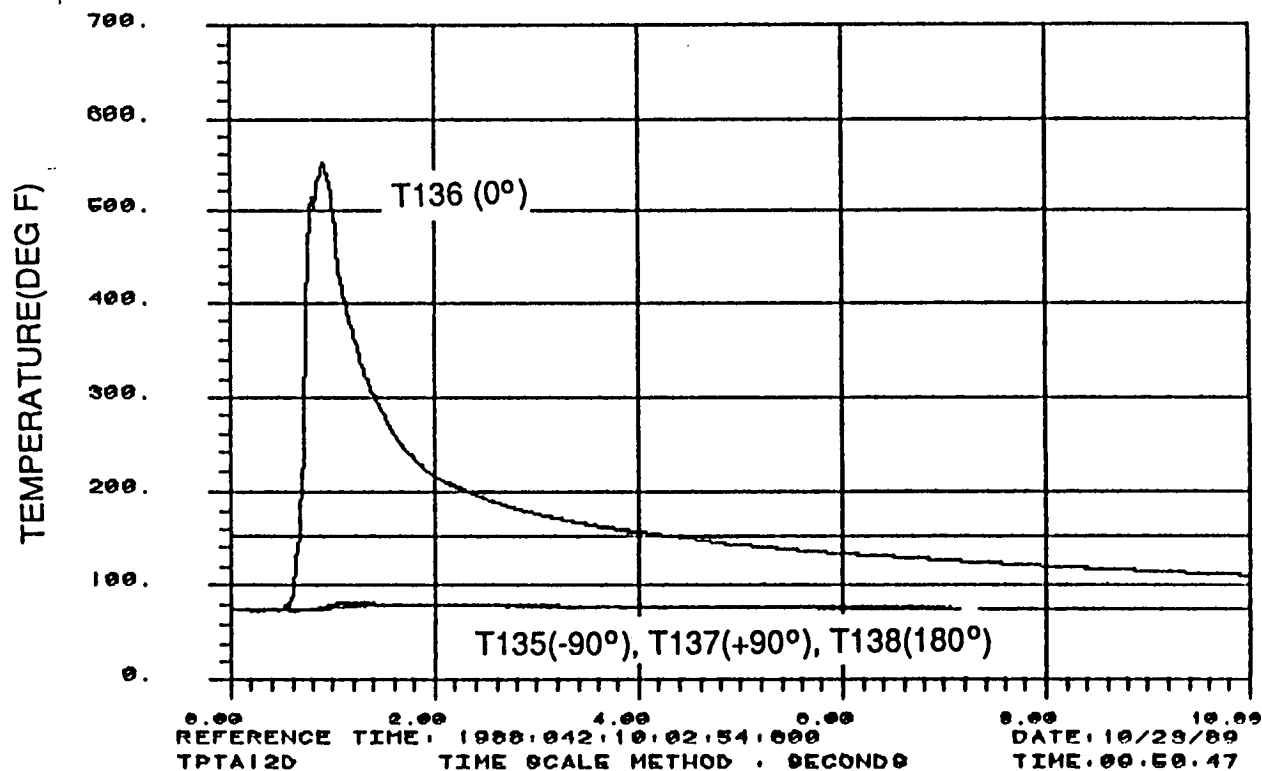
### Comparison of Primary Seal Temperatures at flaw for TPTA 2.3 and TPTA 1.2 Nozzle/Case Joints



## TPTA 2.3 FINAL DATA REVIEW



### Circumferential Distribution of Primary Seal Temperature for TPTA 1.2 Nozzle/Case Joint



# TPTA 2.3 FINAL DATA REVIEW



## ***Comparison with Analytical Results***

### Joint A

☐ Flaw geometry

Analysis matched TPTA 2.3 Joint A flaw geometry

☐ Capture feature pressure traces

No test data available

☐ Capture feature temperature traces

No test data available

Analytical results show circumferential thermal gradient to  
90° from flaw

### Joint D

☐ Flaw geometry

TPTA 2.3: 0.35" wide polysulfide defect, 1" wiper O-Ring flaw

Analysis: 0.75" wide polysulfide defect, 1" wiper O-Ring flaw

☐ Primary pressure traces

At flaw: TPTA 2.3 data lagged analytical results

± 90° from flaw: TPTA 2.3 data asymmetric and far below analytical results

☐ Primary temperature traces

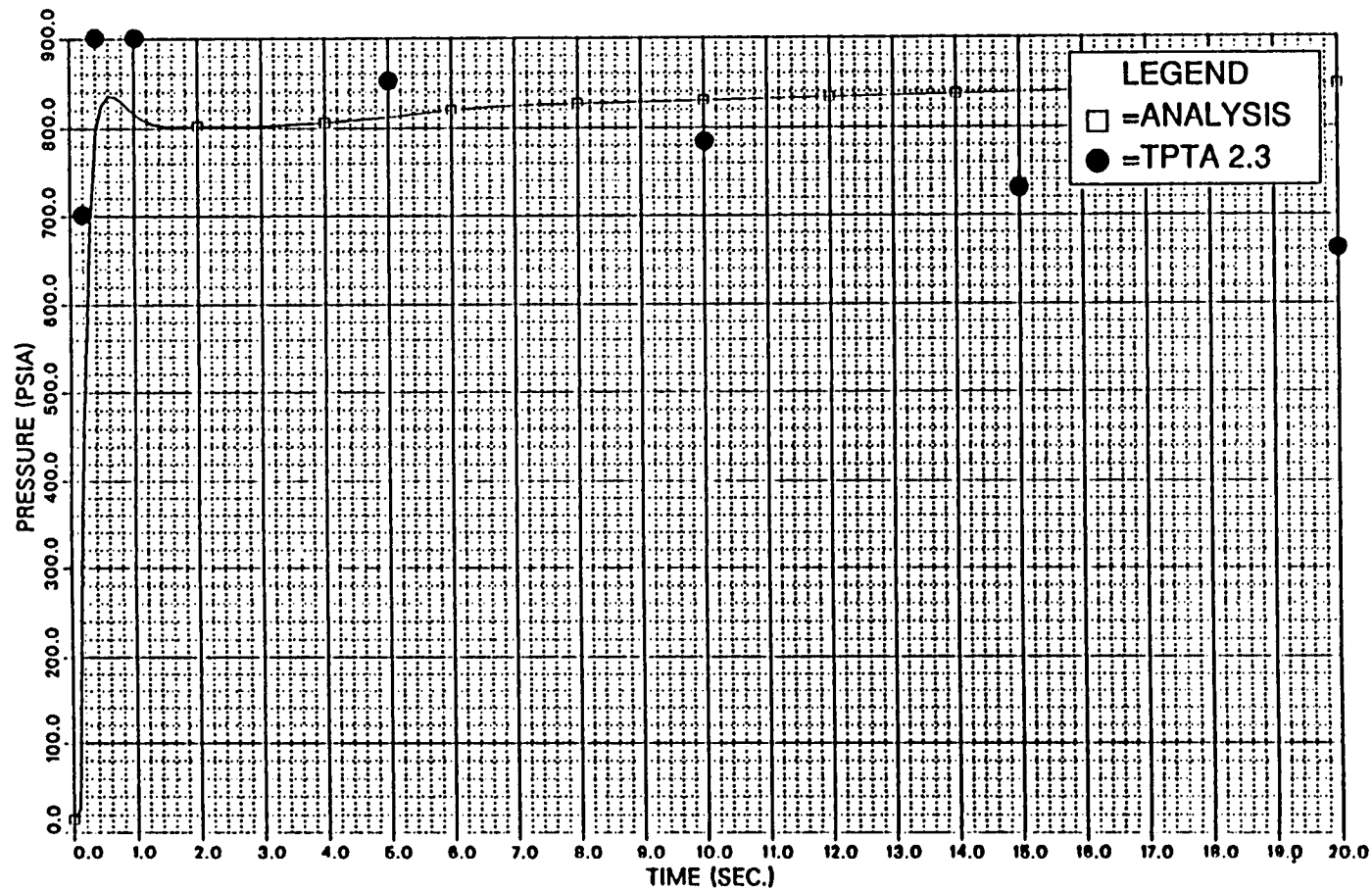
TPTA 2.3 data constant at 70°F

Analytical data exhibits severe circumferential thermal gradient to 90° from flaw

# TPTA 2.3 FINAL DATA REVIEW



## Bore Pressure

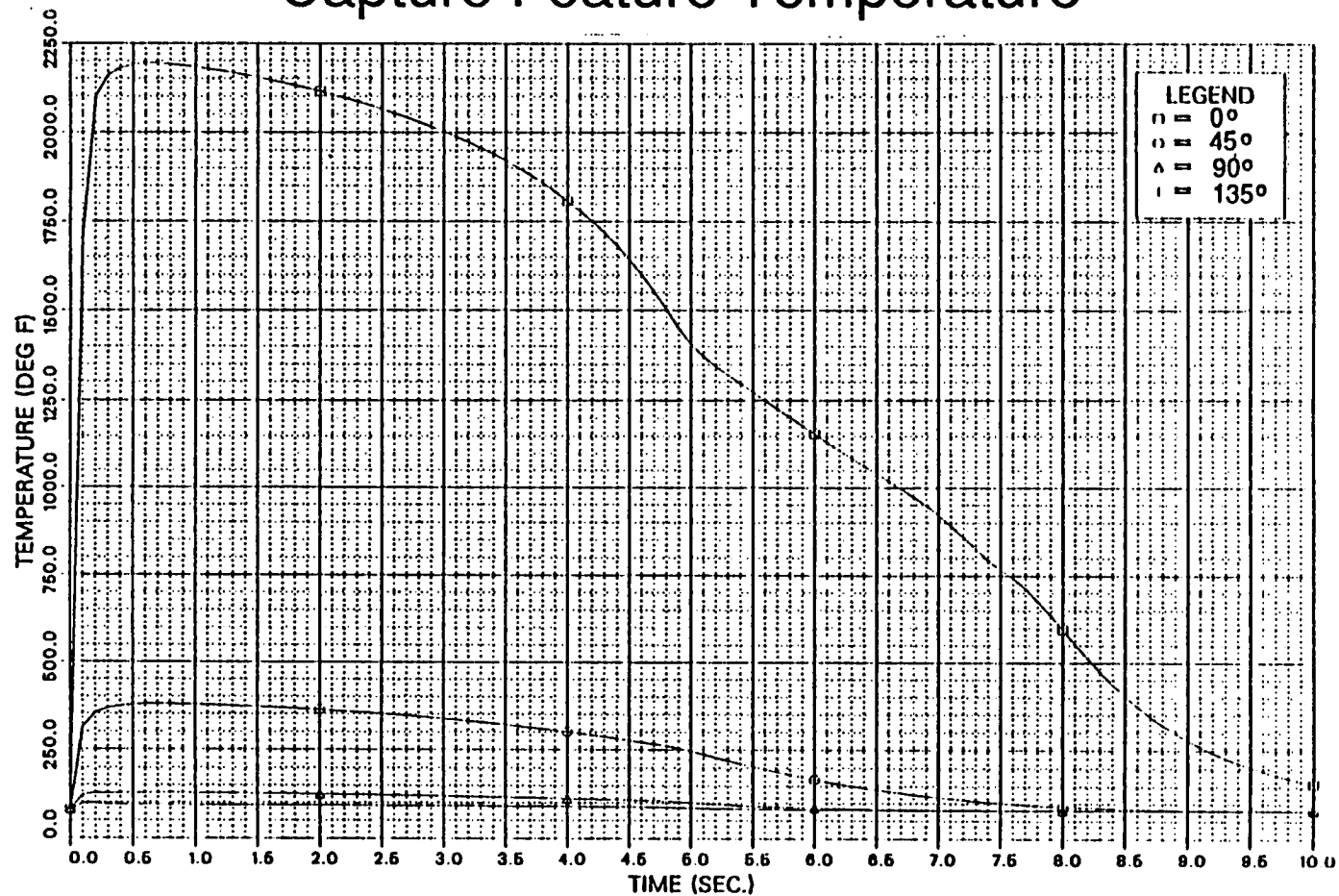




# TPTA 2.3 FINAL DATA REVIEW



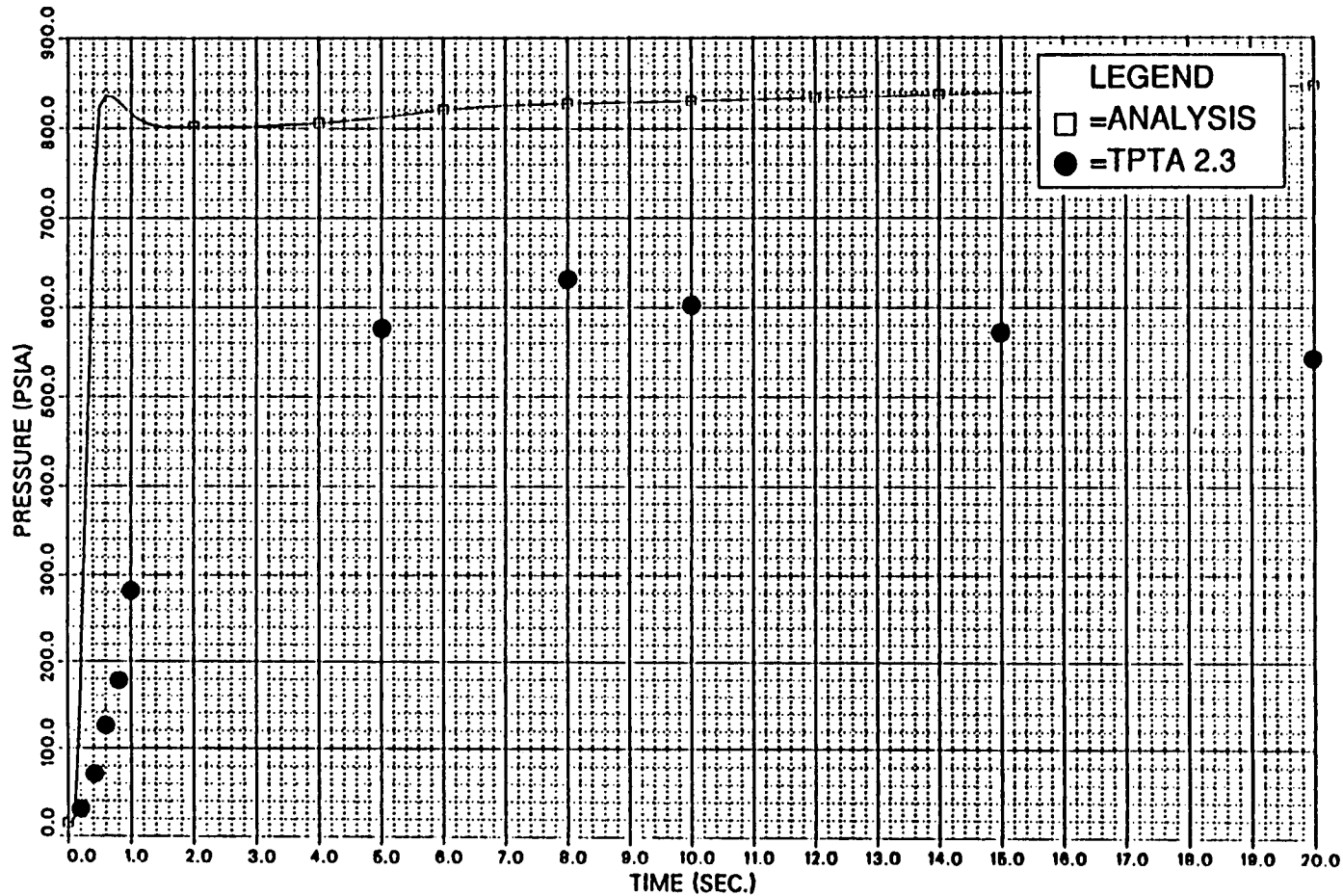
## Computed Circumferential Variation of Capture Feature Temperature



# TPTA 2.3 FINAL DATA REVIEW



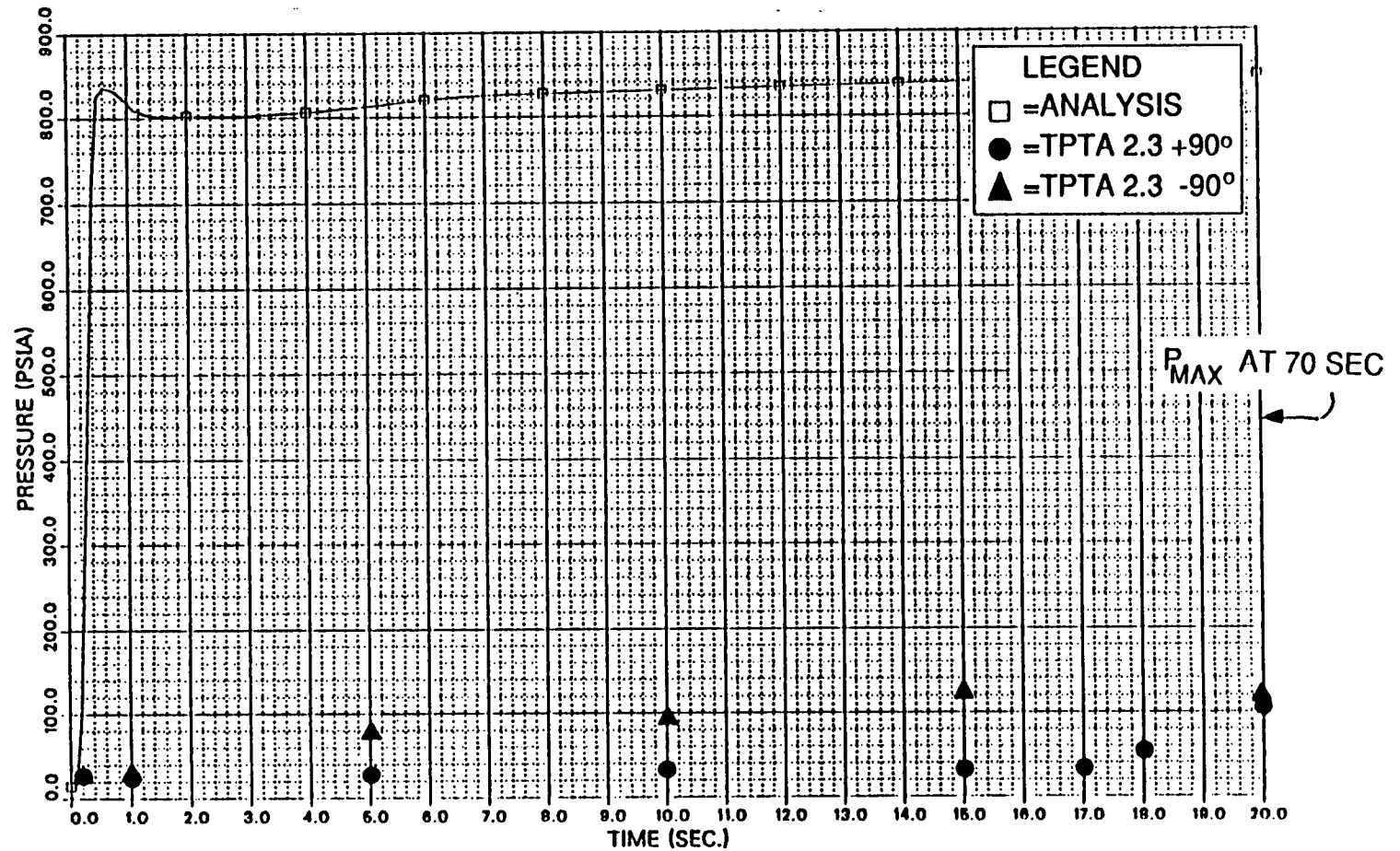
## Primary Seal Pressure at Flaw



# TPTA 2.3 FINAL DATA REVIEW



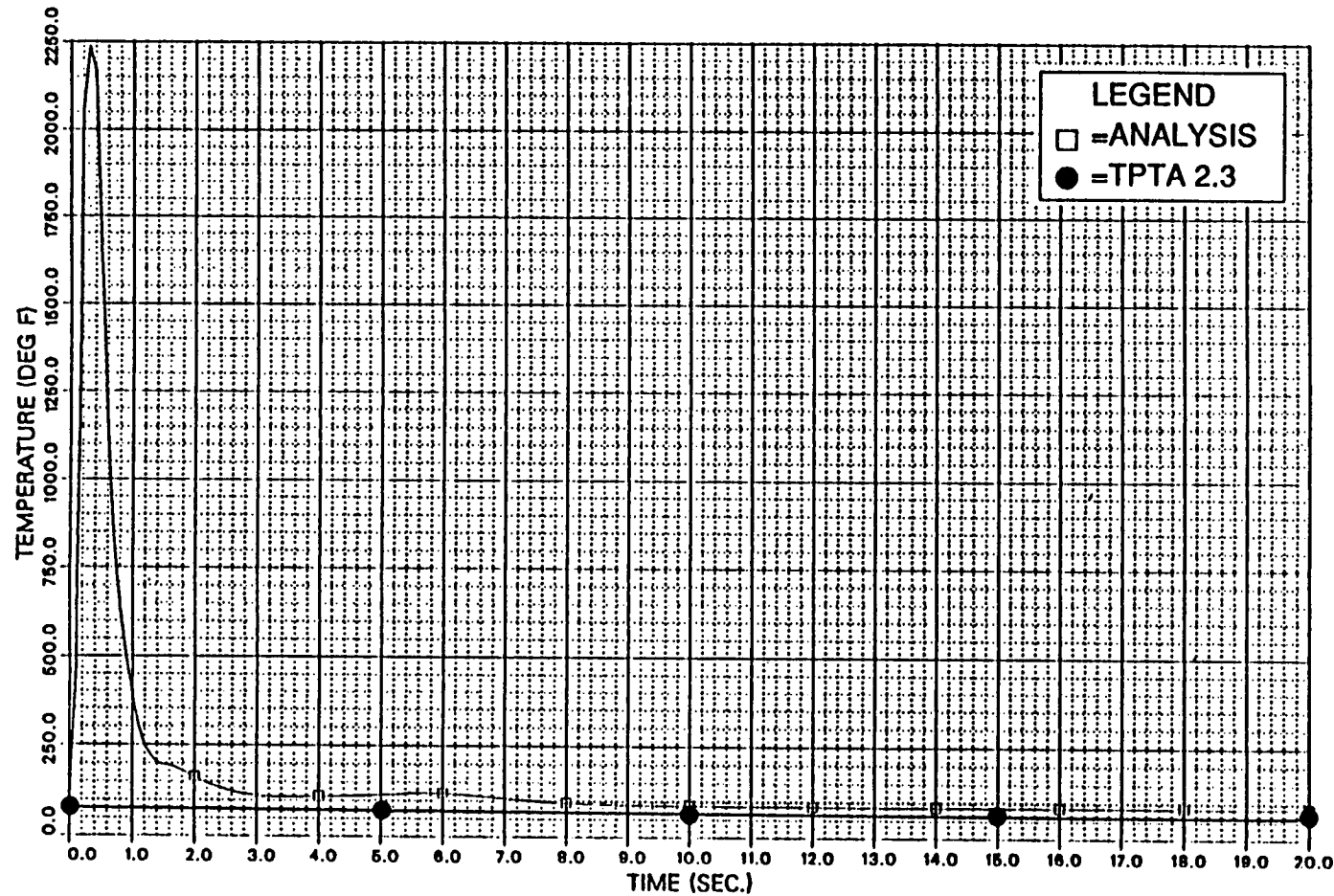
## Primary Seal Pressure at 90° from Flaw



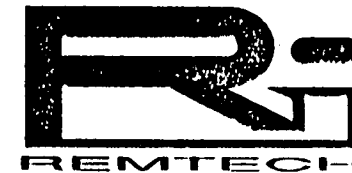
# TPTA 2.3 FINAL DATA REVIEW



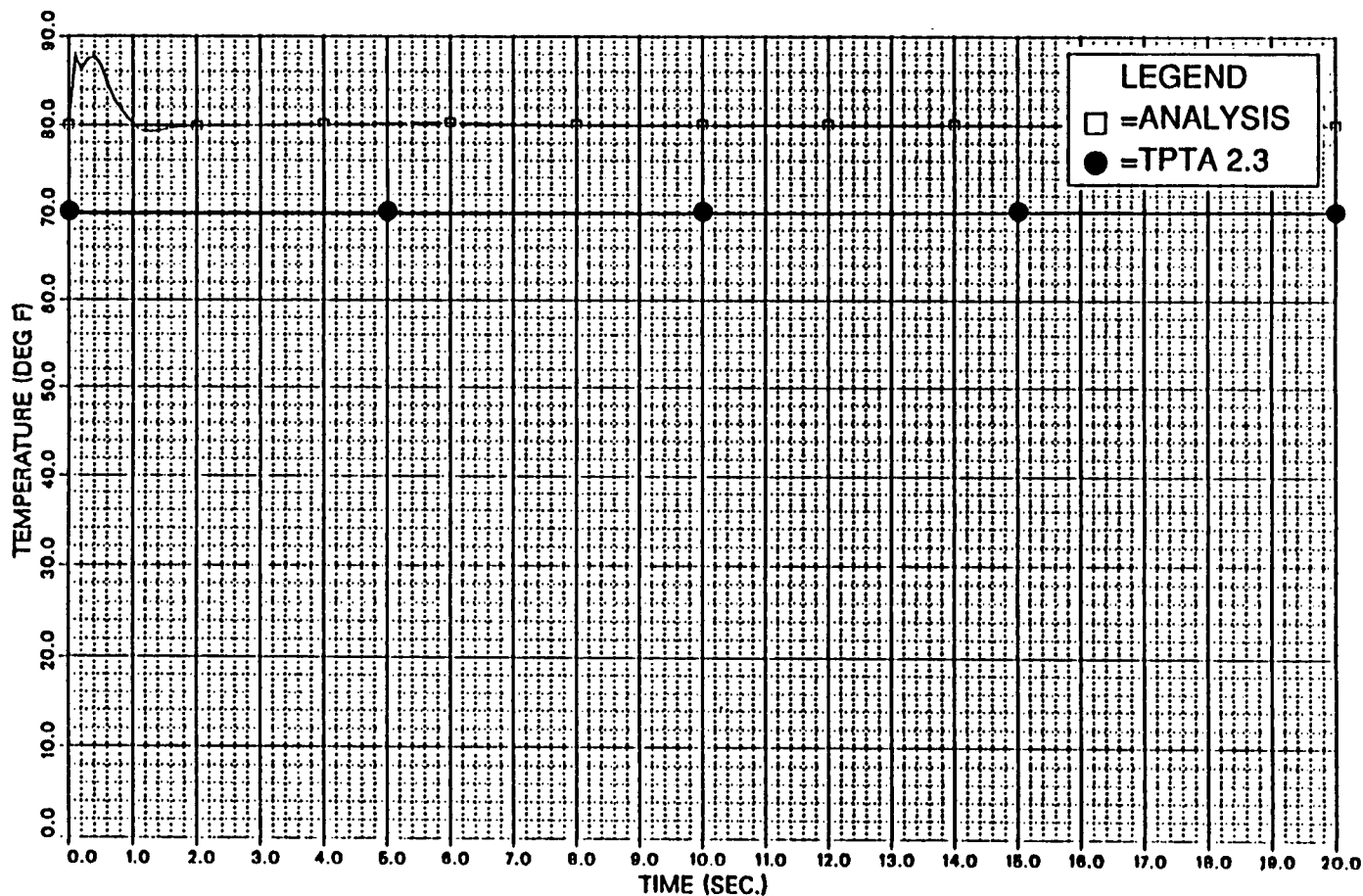
## Primary O-ring Gland Temperature at Flaw



## TPTA 2.3 FINAL DATA REVIEW



### Primary O-ring Gland Temperature 90° from Flaw



## TPTA 2.3 FINAL DATA REVIEW



### ***Adequacy of Test Data***

#### Non-test joints

- ☐ Instrumentation quantity and placement are adequate for historical data base

#### Joints A, B, and D

- ☐ Instrumentation quantity and placement are inadequate because:
  - high fatality rate
  - insufficient to establish flow property gradients
- ☐ Need more redundancy of measurements
- ☐ Need additional pressure and temperature measurements between  $0^\circ$  and  $\pm 90^\circ$  from flaw
- ☐ Types of transducers and installation procedures need to be reviewed

## **Appendix 3**

### **TPTA 2.3 FINAL DATA REVIEW MINUTES**

George C. Marshall Space Flight Center  
Marshall Space Flight Center, Alabama 35812  
AC(205)544-2121

to Attn of: EP54 (89-140)

October 30, 1989

TO: Distribution

FROM: EP54/Mr. Domal

SUBJECT: Final Data Review for TPTA 2.3

The meeting was held on Tuesday, October 24, 1989, at 8:30-11:30 a.m. in room 243, building 4666.

The attendees are listed in enclosure, and are included in the distribution list. All handouts are available at my Office.

Messrs. Domal, Goldberg, Bauman, and Ross made introductory remarks.

a. Mr. Domal covered the test hardware status, monitored during destacking operations. No damaged hardware was noted. The small flaw in the joint "A" J-seal showed a tendency to erode the filler material up to the dimensions of a previous large flaw at this same location. An action item was issued to determine if this filler is also used in flight operations at KSC. The intentional flaw in the wiper o-ring was not damaged because polysulfide flowed into the flawed joint and reduced the hot gases flowing through the flawed o-ring.

b. Mr. Bauman summarized the final data processing and gave its format. The EP54 data base on the Perkin-Elmer system includes reduced data for all TPTA firings. The data is at conditions required by MSFC analyst. Mr. Bauman summarized igniter pressure data. There was no anomalous results; data quality was satisfactory, it complies with Thiokol performance Specification, and no instrumentation changes recommended.

c. Mr. Bugg presented the displacement data, more specifically the joint primary/secondary gap deflection at a high (2000 s/sec) sampling rate. All gap openings were within the experience base. The higher sampling rate did show greater detail but no new phenomena.

d. Mr. Hill summarized the strain gage data, stating that TPTA performance was nominal and there were no hardware anomalies. He stated that although there is always some bad



data, there was enough data to show creditabililty and comparison to previous tests. He had no future test requirements.


e. Mr. Bacchus was represented by REMTECH, Mr. Woods stated essentially no results from the test joints A, B, and D because instrumentation was inadequate. He was responsible for gas flows and thermal behavior in joints.

f. Mr. Dallas Clark, who analyzed the same type of data, stated that on joint "A" capture feature o-ring sealed (verified by  $V_2$  and  $V_4$  instrumentation. Because of the TPTA 2.3 temperature data deficiency which was typical of prior TPTA data, the call for an instrumentation improvement effort was a good idea.

g. Mr. Uttam Gill presented the same data for joint "D". The analysis was in general agreement. The polysulfide flowed into the flaw in the wiper o-ring. He also pleaded for improved temperature and pressure instrumentation in the joint cavities.

h. Mr. Dick Brolliar presented the skirt strain gage data. Ninety-four strain gages were required, and the data is adequate to assess structural response to TPTA loads. All strain plots were well behaved. Peaks generally occur within the first 0.5 second. Good correlation with previous tests. Fatigue loading (static) is fairly benign. There are no serious concerns indicated by data on aft skirt.

i. In summary, this firing of TPTA was the best of all TPTA firings with respect to data acquisition and still the joint cavity instrumentation left something to be desired. In the near future, we will propose a series of meetings to see what recommendations are offered and which ones we can implement with respect to instrumentation quality.



A.F. Domal  
Solid Propulsion Branch

Enclosure

Distribution:

EE11/Mr. Smith  
EE51/Messrs. Davis/Jones  
ED01/Dr. Blair  
ED22/Messrs. Hill/Richard  
ED24/Mr. Broliar  
ED25/Mr. Bianca  
ED33/Mr. Bugg  
ED64/Messrs. Fisher/Clark  
EH01/Mr. Schuerer  
EL01/Mr. Chubb  
EB01/Mr. McMillion  
SA43/Mr. Rutland  
EP01/Mr. McCarty  
EP51/Mr. Redus  
EP65/Mr. Bechtel  
EP54/Messrs. Goldberg/Holt  
EP73A/Messrs. Skates/Porter  
MMC/Messrs. Bauman/Story  
NTI/Mr. Phillips  
Attendees

FINAL DATA REVIEW FOR TPTA 2.3  
OCTOBER 24, 1989  
8:30-11:30 A.M.  
BUILDING 4666, ROOM 243

NAME	ORGANIZATION	TELEPHONE
George Story	MMC	4-7618
Fred P. Bickley	MSFC/EH02	4-2491
Bob Porter	Wyle/EP76	4-1163
Roy Skates	Wyle/EP76	4-1448
Ron Lancaster	Wyle/EP76	4-1343
Frank Bugg	ED22	4-1502
Darrell DeWeese	EH33	4-8962
Uttam Gill	ED64	4-5245
Mark Hill	ED24	4-4327
Melvin R. Phillips	NTI	4-5079
Dallas W. Clark	MSFC/ED64	4-9521
Ben Goldberg	EP54	4-2683
Jim Parker	EL01	4-2340
Charles Martin	EP54	4-7098
Dan M. Holt	EP54	4-4949
Diane Miller	EP54	4-7357
Bob Bauman	MMC	4-5297
Hamilton Woods	REMTECH	536-8581
E.C. Knox	REMTECH	536-8581
Dave Bacchus	ED33	4-1567
Mack Ross	EE53	4-5587
A.F. Domal	EP54	4-8757

## **Appendix 4**

### **FIELD JOINT INSTRUMENTATION IMPROVEMENTS MEETING**

George C. Marshall Space Flight Center  
Marshall Space Flight Center, Alabama 35812  
AC(205)544-2121

Attn of: EP54 (90-16)

January 19, 1990

TO: EP54/Mr. Goldberg  
FROM: EP54/Mr. Domal  
SUBJECT: Field Joint Instrumentation Improvement Meeting

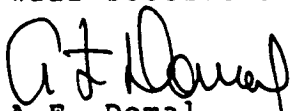
A meeting was held in building 4666, on January 18, 1990. The purpose of the meeting was to address the lack of reliable temperature measurements in the V1 volume at lip of the J-seal. Those in attendance were:

Dave Bacchus	-	MSFC
Gene Knox	-	REMTECH
Hamilton Woods	-	REMTECH
A.F. Domal	-	MSFC

These temperature measurements in joint "A" have a poor history of performance. An inspection of the joint indicates the thermocouples were buried in the lip of the J-seal making it impossible to sense gas temperature.

It was agreed that cutting a small scallop in the lip of the J-seal and centering the junction bead in the center would measure the gas temperature in the flawed joint. All agreed that 10 mil T/C wire would do the job. It was also agreed that the flaw in the J-seal should be the small (narrow) and my requirement was accepted that the C.F. o-ring should be flawed as this joint will be cold temperature conditioned. It was also agreed to rotate the flaw in the J-seal to a new location away from the old J-seal flaw if there is one in the #1 hardware.

REMTECH will forward a recommendation based on this meeting, it will receive a second review that that time.



A.F. Domal  
Solid Propulsion Branch

cc:  
EP54/Mr. Holt  
REMTECH/Messrs. Bacchus/Knox/Woods

## **Appendix 5**

### **TPTA 1.4 TEST REQUIREMENTS**

REMTECH MEMORANDUM

---

**TITLE:** TPTA 1.4 Test Requirements

**DATE:** April 2, 1990

**AUTHOR:** G. Hamilton Woods

**CONTRACT NO.:** NAS8-37891

**PREPARED FOR:** Mr. Benjamin Goldberg, NASA/MSFC

---

In order to meet TPTA test objectives, specifically, the objectives to establish an SRM joint performance historical data base and to provide data for analytical model validation, the test joints need to be instrumented with gas sensing pressure transducers, gas sensing thermocouples, and steel surface thermocouples.

Several instruments are needed in the vicinity of each flaw to establish flow property gradients. Instruments should be located on both sides of each flaw to record non-symmetric flow patterns and to allow for data loss.

The data sampling rate of 80 samples/second used in previous TPTA tests is sufficient to capture both gas pressure and gas temperature transients.

The required instrument responses are based on the expected rise rates of gas pressure, gas temperature, and steel surface temperature in the test joints. These requirements were established based on previous test measurements and on analytical results.

The required measurement ranges of the transducers are based on previous test measurements and on analytical results.

The required accuracy of the transducers is determined from the ability of previous analytical results to track previous test results.

The previous TPTA test (TPTA 2.3) J-seal flaw in joint A ablated to the dimensions of the repair material. This ablation was excessive compared to J-seal ablation in virgin material. This excessive ablation causes three things to happen: the jet velocity into the test joint is lower because the flow area is larger; the fill time is shorter because the flow rate is greater; and the gas temperature is reduced because more energy is removed when the ablation rate is higher. The effects are to reduce O-ring erosion and to possibly avoid heat affect on the tang that might otherwise have occurred. The result may be a test joint that

has an unacceptably benign thermal environment. Unless the excessive ablation problem can be solved, it may be necessary to place the J-seal flaw in virgin material. One possible repair mechanism is to remove the section of the J-seal that has the used flaw and replace it with virgin material.

## Gas Pressure Sensing Transducers

Gas pressure sensing transducers need to be installed in the capture feature of joints A and B, in the V2 region of joints A and B, in front of the wiper O-ring in joint D, and in front of the primary O-ring in joint D. (See Fig.1 and Fig.2.)

The spacing of the transducers is as follows:

- 7 transducers between  $\pm 45^\circ$ , one in line with the J-seal or polysulfide flaw, the other locations to be determined
- $\pm 90^\circ$  from flaw
- $180^\circ$  from flaw

The required sampling rate of all transducers is 80 samples/second.

The desired response time of all transducers is 5000 psi/second.

The required measurement range of all transducers is 0 – 1000 psi.

The required accuracy of all transducers is  $\pm 0.5\%$ .

## Gas Temperature Sensing Thermocouples

Gas temperature sensing thermocouples are needed in the capture feature of joints A and B, in the V2 region of joints A and B, in front of the wiper O-ring in joint D, and in front of the primary O-ring in joint D. (See Fig.1 and Fig.2.)

The spacing of the transducers is as follows:

- 7 transducers between  $\pm 45^\circ$ , one in line with the J-seal or polysulfide flaw, the other locations to be determined
- $\pm 90^\circ$  from flaw
- $180^\circ$  from flaw

The required sampling rate of all thermocouples is 80 samples/second.

The desired response times of the thermocouples are as follows:



- between  $\pm 45^\circ$  from the flaw: 20000°F/second
- $\pm 90^\circ$  and  $180^\circ$  from flaw: 5000°F/second

The required measurement ranges of the thermocouples are as follows:

- in line with flaw: 0 – 4000°F
- between  $\pm 45^\circ$  from flaw: 0 – 3000°F
- $\pm 90^\circ$  and  $180^\circ$  from flaw: 0 – 1000°F

The required accuracy of all thermocouples is  $\pm 5\%$  of full scale.

## Surface Temperature Sensing Thermocouples

In order to adequately assess the flow properties of the combustion gases in the test joints, the energy removed by convection from the combustion gases to the steel surfaces needs to be accounted for. Convection models can be validated by comparing the steel surface temperatures resulting from analysis with those obtained from test data. Knowledge of the steel temperatures in some regions (e.g. on the capture hook edge) is needed to verify that the temperatures remain well below maximum limits. The steel surface temperatures are needed in line with the J-seal flaw on the capture hook edge and in the interference gap between the capture feature and primary O-rings in joints A and B. A steel surface temperature measurement is also needed in line with the polysulfide flaw between the wiper and primary O-rings in joint D. (See Fig.1 and Fig.2.)

The required sampling rate of all steel surface thermocouples is 80 samples/second.

The desired response time of all steel surface thermocouples is 5000°F/second.

The required measurement ranges of all steel surface thermocouples is 0 – 3000°F.

The required accuracy of all steel surface thermocouples is  $\pm 5\%$  of full scale.

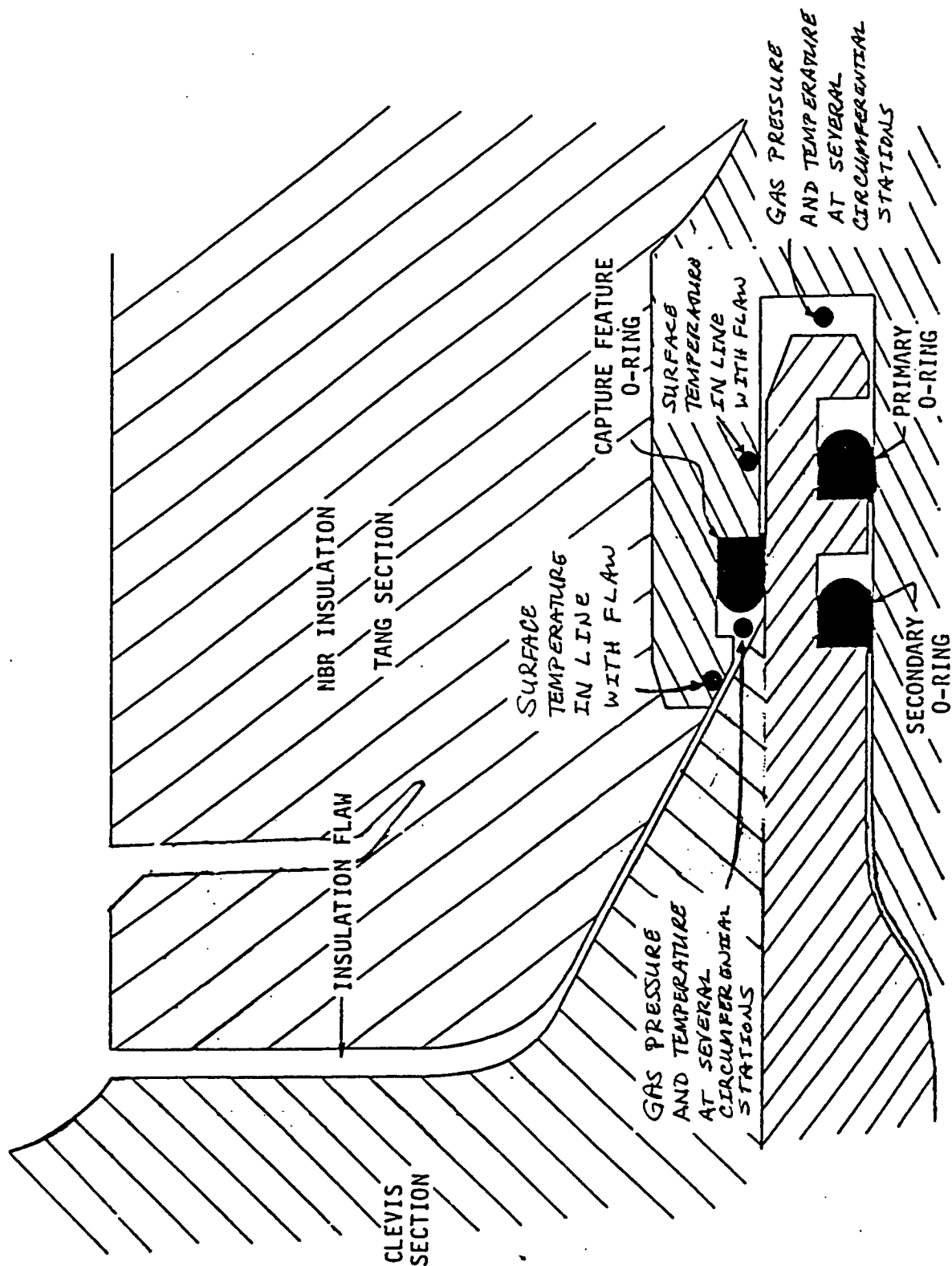


Figure 1: Field Joint Instrumentation Layout

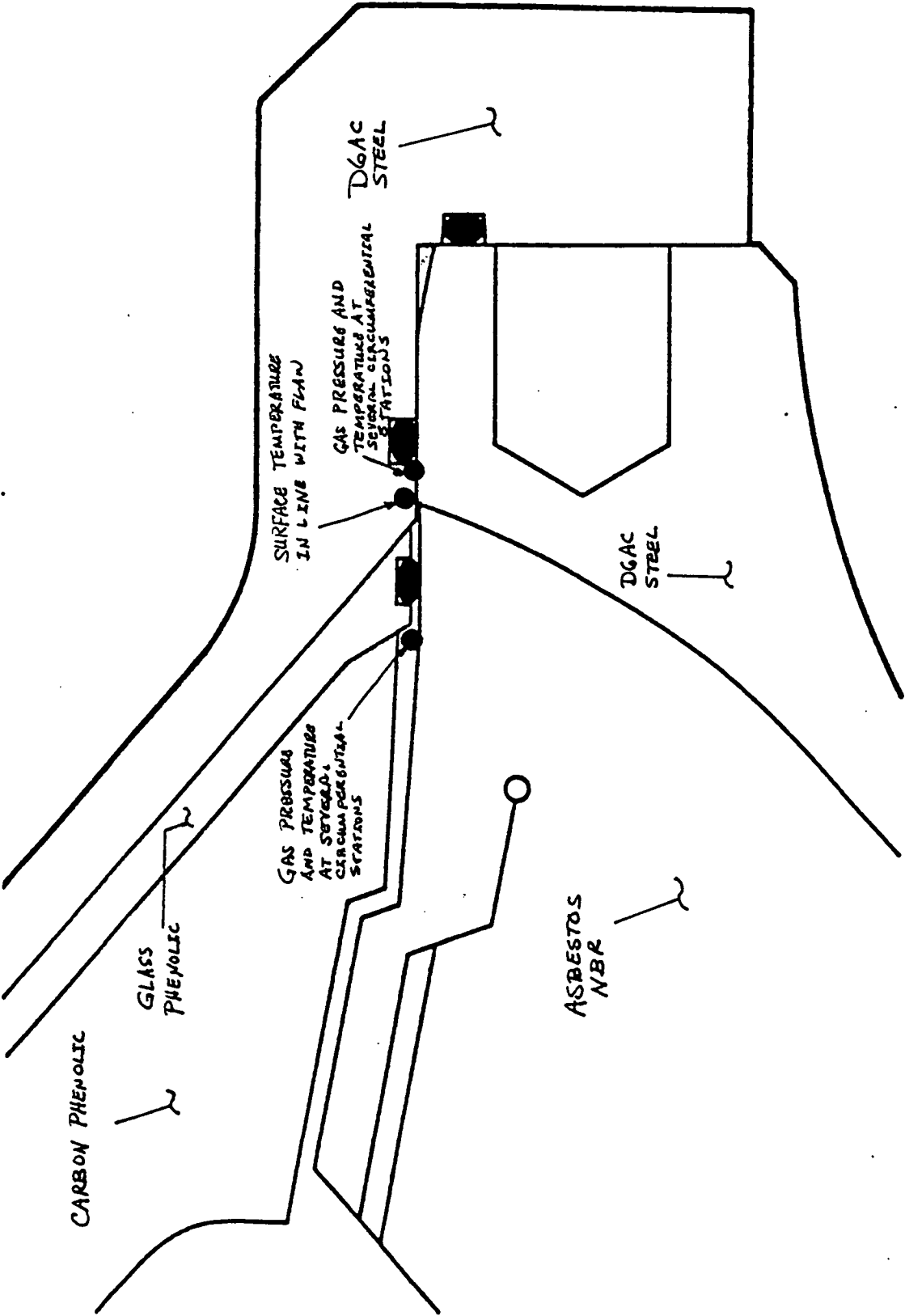


Figure 2: Nozzle/Case Joint Instrumentation Layout

## **Appendix 6**

### **DOCUMENTATION OF TPTA HARDWARE**

George C. Marshall Space Flight Center  
Marshall Space Flight Center, Alabama 35812  
AC(205)544-2121

to Attn of:

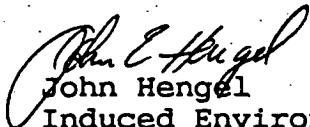
ED33(84-90)

July 25, 1990

TO: EE54/Tom Williams  
FROM: ED33/John Hengel  
SUBJECT: Documentation of TPTA Hardware

Enclosed please find REMTECH memorandum RM213-02, entitled "Recommended TPTA Hardware Modifications." This memorandum documents the need for additional instrumentation on the TPTA hardware.

I concur with these recommendations and solicit your support for this activity. If you wish to discuss them with me or have any questions, please call me at 4-1570 or Hamilton Woods of REMTECH at 536-8581.

  
John Hengel

Induced Environments Branch

APPROVAL:



Werner K. Dahm  
Chief, Aerophysics Division

Enclosure

cc:  
EP54/Mr. Goldberg  
ED01/Dr. Blair  
ED31/Mr. Dahm/Mr. Andrews  
ED33/Mr. Foster/Mr. Bacchus/File  
Remtech/Mr. Knox/Mr. Woods  
Wyle/Mr. King

REMTECH MEMORANDUM

---

**TITLE:** Recommended TPTA Hardware Modifications

**DATE:** July 23, 1990

**AUTHOR:** G. Hamilton Woods

**CONTRACT NO.:** NAS8-37891

**PREPARED FOR:** Mr. Tom Williams, NASA/MSFC

---

MSFC obtained the TPTA hardware from Morton Thiokol prior to TPTA test 2.3. The history before that test is not well known, but REMTECH, in support of ED33, has been unable to obtain sufficient information from the MSFC-run TPTA test (TPTA 2.3) to analyze test performance. Because the TPTA hardware is vital to both RSRM and ASRM programs, it is recommended that additional gas pressure and temperature sensing transducers be installed on the TPTA hardware to obtain the needed information.

The purpose of the TPTA program is to provide test data which can be used to increase the reliability of the data used to verify the sealing capability of RSRM joints. In support of the TPTA tests, analytical work has been done to accomplish the following program objectives:

- Demonstrate the ability of the nozzle-to-case joint seal system, in a fail-safe mode with pressure on the primary O-ring, to provide a pressure seal while accomodating structural deflections during the ignition pressure transient,
- Demonstrate that the field and nozzle-to-case joint insulation maintains structural integrity during assembly except as a result of any intentional insulation/case unbonds, and
- Establish SRM joint performance historical data base and provide data (gas pressure and temperature measurements) for analytical model validation.

The test data from TPTA test 2.3 did not supply enough information to establish an SRM joint performance historical data base or to provide data for analytical model validation. The instrumentation quantity and placement were inadequate due to a high fatality rate and an insufficient quantity to establish flow property gradients in the test joints. The gas temperatures in the capture feature of the field joint and in the wiper O-ring groove of the nozzle/case joint, for instance, drop very steeply circumferentially in the first 45° from the flaw. The gas pressure drop is not so pronounced, unless significant plugging occurs in the joint. Several instruments are needed in the vicinity of each test flaw to establish flow property gradients. Instruments should be located on both sides of each flaw to record asymmetric flow patterns and to compensate for data loss.

Wyle Laboratories is responsible for the TPTA hardware. Locations for the additional instrumentation have been proposed to Wyle Laboratories in REMTECH Memorandum RM 213-01, "TPTA 1.4 Test Requirements," which is appended to this note. Mr. Austin King of Wyle has indicated that installing additional instrumentation on the TPTA hardware will require hardware modifications. He has also indicated that such modifications could not be performed by Wyle within current resources, and that additional funding is necessary in order to proceed with the installation of new instrumentation.

At the TPTA 1.4 Test Requirements meeting of March 22, 1990, it was suggested that any hardware modifications necessary to accomplish program objectives be brought to the attention of the RSRM projects office. Details of the modifications necessary can be provided by Mr. Austin King of Wyle.

REMTECH MEMORANDUM

---

**TITLE:** TPTA 1.4 Test Requirements

**DATE:** April 2, 1990

**AUTHOR:** G. Hamilton Woods

**CONTRACT NO.:** NAS8-37891

**PREPARED FOR:** Mr. Benjamin Goldberg, NASA/MSFC

---

In order to meet TPTA test objectives, specifically, the objectives to establish an SRM joint performance historical data base and to provide data for analytical model validation, the test joints need to be instrumented with gas sensing pressure transducers, gas sensing thermocouples, and steel surface thermocouples.

Several instruments are needed in the vicinity of each flaw to establish flow property gradients. Instruments should be located on both sides of each flaw to record non-symmetric flow patterns and to allow for data loss.

The data sampling rate of 80 samples/second used in previous TPTA tests is sufficient to capture both gas pressure and gas temperature transients.

The required instrument responses are based on the expected rise rates of gas pressure, gas temperature, and steel surface temperature in the test joints. These requirements were established based on previous test measurements and on analytical results.

The required measurement ranges of the transducers are based on previous test measurements and on analytical results.

The required accuracy of the transducers is determined from the ability of previous analytical results to track previous test results.

The previous TPTA test (TPTA 2.3) J-seal flaw in joint A ablated to the dimensions of the repair material. This ablation was excessive compared to J-seal ablation in virgin material. This excessive ablation causes three things to happen: the jet velocity into the test joint is lower because the flow area is larger; the fill time is shorter because the flow rate is greater; and the gas temperature is reduced because more energy is removed when the ablation rate is higher. The effects are to reduce O-ring erosion and to possibly avoid heat affect on the tang that might otherwise have occurred. The result may be a test joint that



has an unacceptably benign thermal environment. Unless the excessive ablation problem can be solved, it may be necessary to place the J-seal flaw in virgin material. One possible repair mechanism is to remove the section of the J-seal that has the used flaw and replace it with virgin material.

## Gas Pressure Sensing Transducers

Gas pressure sensing transducers need to be installed in the capture feature of joints A and B, in the V2 region of joints A and B, in front of the wiper O-ring in joint D, and in front of the primary O-ring in joint D. (See Fig.1 and Fig.2.)

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- $\pm 90^\circ$  from flaw
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The required measurement range of all transducers is 0 – 1000 psi.

The required accuracy of all transducers is  $\pm 0.5\%$ .

## Gas Temperature Sensing Thermocouples

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- between  $\pm 45^\circ$  from the flaw: 20000°F/second
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The required accuracy of all thermocouples is  $\pm 5\%$  of full scale.

## Surface Temperature Sensing Thermocouples

In order to adequately assess the flow properties of the combustion gases in the test joints, the energy removed by convection from the combustion gases to the steel surfaces needs to be accounted for. Convection models can be validated by comparing the steel surface temperatures resulting from analysis with those obtained from test data. Knowledge of the steel temperatures in some regions (e.g. on the capture hook edge) is needed to verify that the temperatures remain well below maximum limits. The steel surface temperatures are needed in line with the J-seal flaw on the capture hook edge and in the interference gap between the capture feature and primary O-rings in joints A and B. A steel surface temperature measurement is also needed in line with the polysulfide flaw between the wiper and primary O-rings in joint D. (See Fig.1 and Fig.2.)

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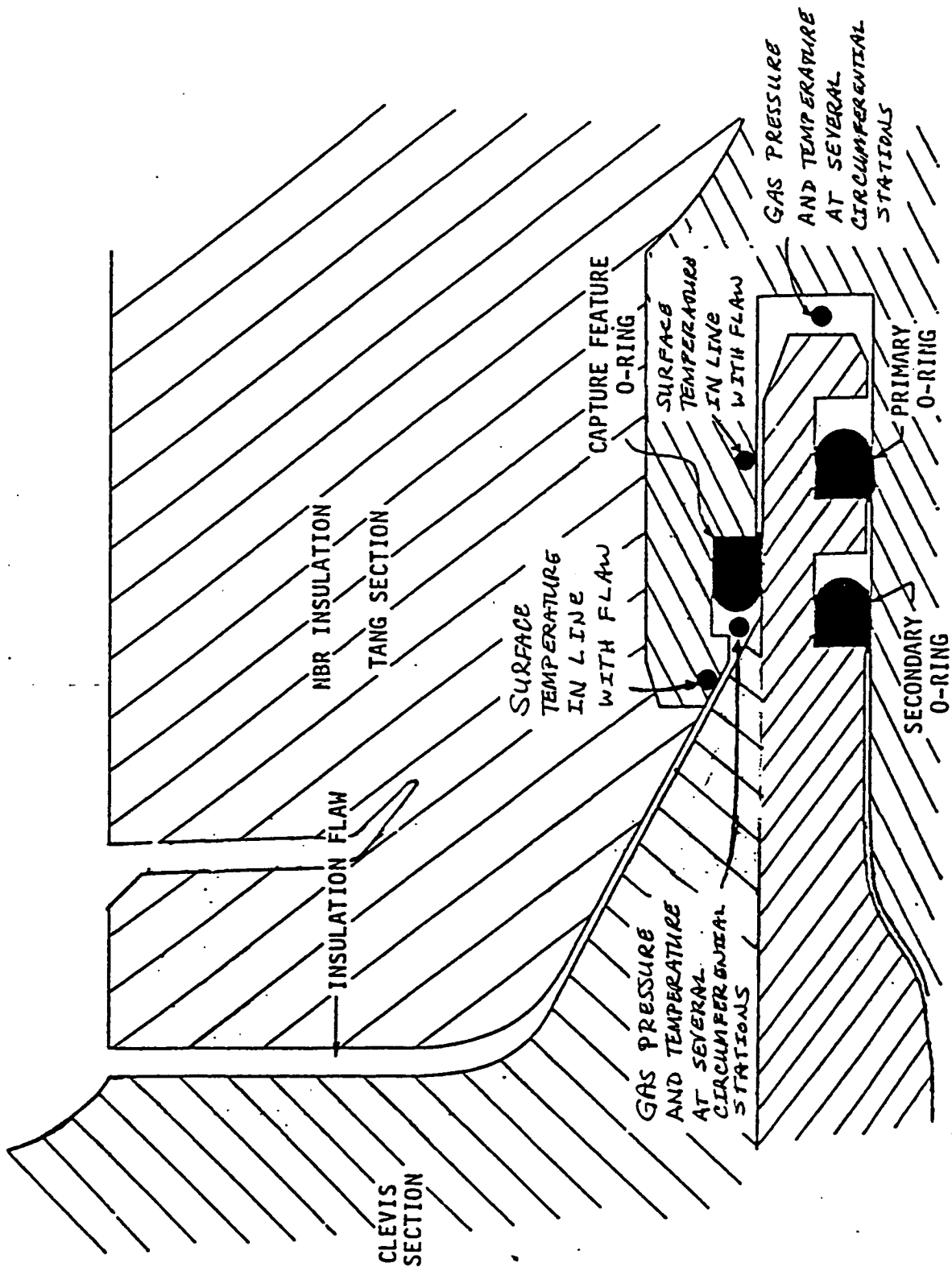


Figure 1: Field Joint Instrumentation Layout

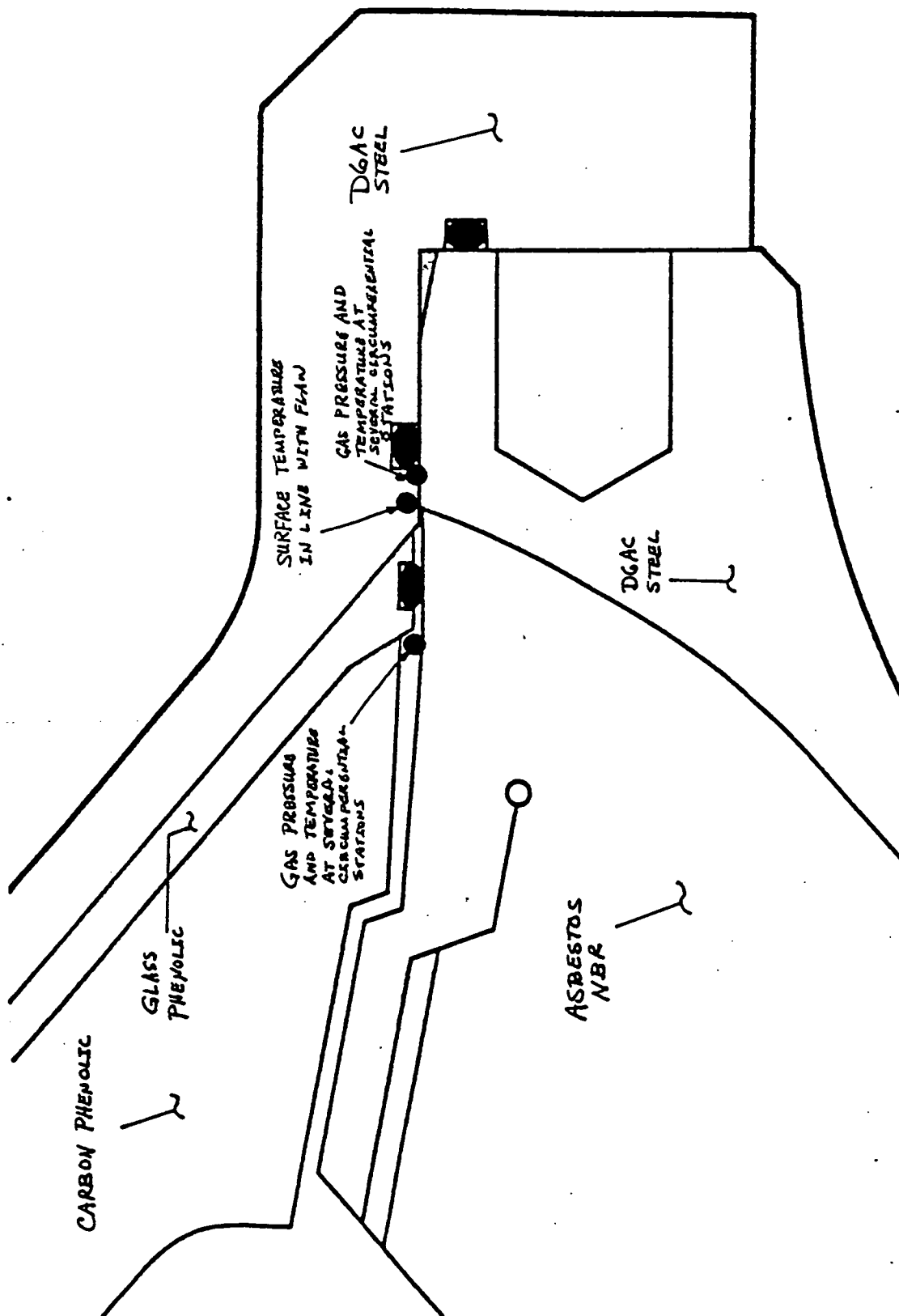


Figure 2: Nozzle/Case Joint Instrumentation Layout

## **Appendix 7**

### **TPTA INSTRUMENTATION REQUIREMENTS ASSESSMENT**

REMTECH MEMORANDUM

---

**DATE:** August 24, 1990

**TO:** John E. Hengel, ED33, NASA/MSFC

**FROM:** Hamilton Woods

**SUBJECT:** TPTA Instrumentation Requirements Assessment

---

This memorandum has been prepared in response to Dr. Jim Blair's inquiry regarding ED33(84-90), a letter to the RSRM Projects Office dated July 25, 1990. The priority of the additional instrumentation does need to be considered. Flight history has shown the RSRM to be successful, but the margins of safety cannot be determined from flight history alone. TPTA history also indicates that the RSRM is successful, but the data have been insufficient to fully assess joint seal performance. The TPTA hardware is scheduled for preliminary development tests of the ASRM and, therefore, needs to be instrumented to obtain flow data.

While attempting to obtain a current TPTA test schedule, REMTECH learned that the RSRM test schedule using the TPTA hardware has been cancelled. According to Mr. Danny Holt of EP54, the TPTA hardware is still planned for preliminary development testing of the ASRM design. The first TPTA test of the ASRM design is currently scheduled for early 1994. In light of this new development, the priority and urgency of installing additional instrumentation on the TPTA hardware are reduced. For use in testing the ASRM design, and in the event the RSRM testing is resumed, the priority of the instrumentation in light of test objectives needs to be determined.

The TPTA test program is intended to provide data for establishing an historical database and for validating analytical techniques. The inadequacy of the instrumentation for collecting the needed data has been demonstrated several times.

In a June 1988 presentation entitled "TPTA Use After 2.2," J.R. Redus, EP51, explained the RSRM testing assessment. He indicated that structural dynamics tests of the field joint were successful and complete but that additional thermal testing is desirable. The key concerns were for an improved simulation of the

full-scale motor and for improved instrumentation. He also outlined objectives for future TPTA tests. Some of the test needs for RSRM were for margin testing of current design limits, effects of process improvements, and validation testing for comparison with analytical results. The existing hardware is planned for the ASRM to test vented joint and igniter joint design improvements and to verify joint dynamics during pressurization and pressures and temperatures at the joints. Specific test objectives were enumerated for each proposed test.

In an August 1988 presentation entitled "TPTA - Continued Testing," Danny Holt, EP54, outlined the RSRM test objectives which called for improved simulation of temperature/pressure at joints. A summary of scheduled tests indicates that six future tests (after TPTA 2.3) are planned for the RSRM hardware, of which two are ASRM preliminary development tests.

In a presentation at the TPTA 2.3 Final Data Review, REMTECH, Inc. compared available joint test data with previous test data and with analytical results. The conclusion of the presentation was that the test data from all of the TPTA tests were inadequate to establish an historical database or to provide data for analytical model validation. Mr. Dallas Clark, ED64, agrees with that assessment.

Without adequate test data it is difficult, if not impossible, to assess test performance. In previous SRM test firings flow anomalies have occurred which would have been difficult to understand without a circumferential distribution of pressure and temperature instrumentation. Also, flow gradients cannot be established without a circumferential distribution of instrumentation.

An objective was established during SRM redesign to develop solid rocket motor internal flow expertise at MSFC. For this reason, the TPTA test hardware was relocated to MSFC prior to TPTA 2.3. Important to SRM internal flow expertise is the development of analytical tools for data comparisons, parametric studies, and assistance in test assessments. Test data are needed to validate these analytical tools and models.

While performing SRM tests builds a confidence in the test configuration, pressure and temperature data are needed to determine safety margins and to assess motor performance. Because testing is expensive and because the TPTA hardware will be used for several tests, it is important to obtain as much data as is needed to meet program objectives.

For continued use of the TPTA hardware in light of current test objectives, the priority of installation of additional instrumentation on the TPTA hardware needs to be assessed.

## **Appendix 8**

### **MODIFICATIONS TO THE TRANSIENT ONE- DIMENSIONAL PIPE-FLOW ANALYZER (TOPAZ) CODE**



## REMTECH TECHNICAL NOTE

---

**SUBJECT:** Modifications to the Transient One-Dimensional Pipe-Flow Analyzer (TOPAZ) Code

**DATE:** September 1991

**AUTHORS:** R. D. Kirchner and G. H. Woods

**CONTRACT NO.:** NAS8-37891

**PREPARED FOR:** Mr. Dave Bacchus, ED33, NASA Marshall Space Flight Center

---

### INTRODUCTION

TOPAZ (Transient One-dimensional Pipe-flow AnalyZer) is a "user-friendly" computer code for modeling the one-dimensional, transient physics of multi-species gas transfer in arbitrary arrangements of pipes, vessels, and flow branches. TOPAZ was developed at the Sandia National Laboratories primarily as a tool for modeling gas flow in conventional weapon gas transfer systems and similar apparatus. Such systems normally consist of complex arrangements of pressure vessels, piping, valves, flow branches, pistons, bladders, and diaphragms.

The version of TOPAZ familiar to most users is documented in considerable detail in the TOPAZ user's guide [1]. Detailed discussions of TOPAZ input requirements, example and code validation problems, and modeling equations and numerics are given in Refs. [2 - 4]. The modeling incorporated in the original and upgrading versions of TOPAZ was sufficient for most conventional gas transfer simulations. Yet these versions lacked the capability to update the wall temperatures during the analyses. These versions were also limited by an inability to output more than six data values in the minor edit subroutine, MINORE.

These limitations led REMTECH to make a number of changes to the TOPAZ code. From the user's viewpoint, this means the addition of several new directives. Interested users should have no trouble adapting to REMTECH's newest version of the code. A list of the most recent input directives may always be obtained from TOPAZAID, the on-line computer generated version of the TOPAZ user's guide. This technical note discusses the coding improvements and additions that were made for TOPAZ by REMTECH through September 1991. Validation of these changes is currently being made. Additional improvements to the code are being contemplated and are discussed in the final section of this note.

## TOPAZ FEATURES

TOPAZ was developed to perform transient analyses of one-dimensional internal fluid flows. Its modeling capabilities include the following features:

- Capability of modeling compressible flows and associated phenomena, including flow choking and the propagation of shock and rarefaction waves,
- Capability of linking flow domains together to form arbitrary arrangements of pipes, valves, flow branches, and vessels,
- Capability of modeling a wide variety of flow boundary conditions, including arbitrary, user-defined boundary conditions,
- Capability of applying a number of constitutive models (e.g., heat transfer coefficients, form loss factors, friction factors, etc.) including user-specified models,
- A high degree of code modularity which permits the addition of new fluid and solid properties, constitutive models, and boundary conditions as the need arises, and
- Fully implicit integration of all model equations without operator splitting, i.e., the same numerical technique is uniformly applied to all equations.

The fluid flow equations were developed with the following assumptions:

- Fluid flow is treated as 1-D and transient,
- Fluid flow is compressible with all local properties constant,
- Heat conduction in the flowing fluid is neglected,
- Multi-dimensional, transient effects associated with convective heat transfer from the containment to the flowing fluid are treated using 1-D, quasi-steady, locally-applied heat transfer correlations,
- Multi-dimensional, transient effects associated with fluid-pipe wall friction are accounted for using 1-D, quasi-steady, locally-applied friction-factor correlations,
- Multi-dimensional, transient effects associated with changes in direction (restrictions, branches, tube bends, etc.) are accounted for using 1-D, quasi-steady, locally-applied form-loss correlations,
- Flowing fluids are non-reacting and do not mix with flowing fluids of different species,
- Viscous dissipation is neglected in the fluid energy equation,
- The effect of standard gravitational acceleration (e.g., 1 g fluid head effects) is included in the fluid flow modeling. However, time and directionally dependent body forces, such as those resulting from angular rotation or linear acceleration of the piping and vessel configuration are not accounted for at this time, and
- Surface temperatures are calculated based on heat conduction into a semi-infinite slab.

## TOPAZ MODIFICATIONS

A summary of the major TOPAZ modifications is given below. A more detailed discussion will follow which describes the derivation and effects of changes and additions to the TOPAZ methodology.

1. **MINOR EDITS FOR ALL PROP VARIABLES:** Users are less restricted with respect to the number of variables and elements that can be printed during minor edits. Early versions of TOPAZ allowed the user to output only six edit variables. REMTECH has modified the MINORE subroutine to allow all PROP variables to be listed for an expanded number of elements during minor edits. One hundred property (PROP) values can now be printed with the program's minor edit subroutine. Identification of minor edit variables and elements are discussed in the program input instructions in the user's guide [1] and its on-line version, TOPAZAID.
2. **DIRECT INPUT OF CHAMBER PRESSURE AND TEMPERATURE TIME HISTORY:** With the requirement to conduct venting analyses with varying reservoir conditions, REMTECH has added the capability to input time histories of both pressure and temperature in TOPAZ. Values for the pressure and temperature vs. time are included in the TOPAZ input file as PVST and TVST, respectively, in the CHAMBER directive.
3. **COUPLED WALL SURFACE TEMPERATURE SOLUTION:** The original version of TOPAZ assumed a constant wall temperature throughout the venting analyses. REMTECH has added subroutine WALL to enable TOPAZ to update the wall temperature as heat energy is transferred between the gas and the wall. This added capability of the program has required the introduction of wall material properties that include the density (RHOW), specific heat (SPHT), and conductivity (CNDW). These parameters must be included in the REGION directives of the input file.
4. **ABLATION TEMPERATURE MODEL:** With the addition of the variable wall temperature model described above, REMTECH has added a restriction for ablating materials that the wall temperature cannot exceed the ablation temperature. The ablation temperature (TABL) must also be included in the input data listing for each region that ablates.
5. **HYDRAULIC DIAMETER INPUT:** REMTECH has modified TOPAZ to allow for the direct calculation of the hydraulic diameter for non-circular cross sections. The hydraulic diameter is calculated from the element perimeter and cross section area.
6. **CROSS SECTION DESIGNATION:** The original TOPAZ code assumed a constant laminar heat transfer Nusselt number that was based on a circular cross section. REMTECH has modified the code to allow for rectangular cross sections as well. A cross section identification flag (ITYP) has been added which specifies the shape of the cross section. When a rectangular cross section has been specified (ITYP=2), the user must also input the maximum cross section dimension (WIDT) to establish the height to width ratio of the cross section.
7. **ENTRANCE EFFECTS:** The original TOPAZ code neglected entrance effects on the heat transfer coefficient. REMTECH has modified the code to allow for the calculation of entrance effects for circular cross sections in laminar flow conditions.

## PRESSURE AND TEMPERATURE HISTORIES

As received from Sandia, TOPAZ included an option for adding heat and/or mass to an element. Mass addition was accomplished such that the mass fraction of the constituent gases remained constant. For a known pressure and time history, supplying

mass and heat addition terms was accomplished by differentiating the perfect gas equation and with respect to time. The slopes of the pressure and temperature time histories were computed and plugged into these equations. The resulting mass and heat addition terms were input to TOPAZ in the form of lookup tables. Interpolation of these tables provided the mass and heat addition terms at a particular time. This procedure was cumbersome and, because of inaccuracies in linear interpolation, the resulting pressure and temperature in the element did not match the input conditions.

### Mass Generation:

Beginning with the ideal gas law, the mass generated per unit volume in a chamber can be expressed in terms of the time rate of change of pressure.

$$\frac{\dot{m}}{V} = \frac{1}{RT} \left( \frac{\partial P}{\partial t} - \frac{P}{T} \frac{\partial T}{\partial t} \right)$$

where  $\dot{m}/V$  is the rate of mass generation per unit volume,  $\partial P/\partial t$  is the time rate of change of pressure,  $\partial T/\partial t$  is the time rate of change of temperature, and  $R$  is the gas constant.  $\dot{m}/V$  is calculated by TOPAZ in subroutine YTYPE1. All units of measurement in TOPAZ are defined in the International System with mass in kilograms, distance in meters, force in Newtons, and energy in Joules.

### Heat Generation:

Similarly, the heat generated per unit volume can be derived from the time rate of change of pressure. This can be expressed in the form

$$\frac{\dot{q}}{V} = \frac{C_v}{R} \frac{\partial P}{\partial t}$$

where  $\dot{q}/V$  is the rate of heat generation per unit volume and  $C_v$  is the specific heat with constant volume. TOPAZ calculates  $\dot{q}/V$  in subroutine YTYPE2.

The equations used to compute mass and heat addition terms were integrated into TOPAZ so that the boundary conditions of pressure and temperature could be input directly. Because only a single interpolation has to be performed at each time step, the computed pressure and temperature more closely match the input values.

## WALL SURFACE TEMPERATURE UPDATES

Heat transfer between flowing gases and their bounding surfaces can lead to significant changes in wall temperatures depending on the heat transfer rate and the thermal properties of the surfaces. TOPAZ was modified in accordance with Goodman's surface temperature approximation presented in Ref. [5] to model such changes in wall surface temperature. This approximation expresses the instantaneous surface temperature ( $T_w$ )

in terms of the initial wall temperature ( $T_o$ ) and the gas temperature ( $T_g$ ) as presented below

$$T_w = T_o - \eta + \left[ (T_o - \eta)^2 + 2\eta T_g - T_o^2 \right]^{1/2}, \text{ where } \eta = \frac{2h_c}{3k^2}H,$$

$h_c$  is the heat transfer coefficient,  $k$  is the conductivity, and  $H$  is the integrated heating load expressed by

$$H = \int_0^t \alpha^* h_c (T_w - T_o) dt \text{ where } \alpha^* \text{ is the thermal diffusivity.}$$

## CIRCULAR VS. NON-CIRCULAR CROSS SECTIONS

Considerable efforts were made to improve the TOPAZ methodology to incorporate features that include:

1. the effect of rectangular cross sections on momentum and heat transfer processes,
2. the effect of Reynolds number on momentum processes, and
3. the effect of surface roughness on heat transfer processes.

These additions to TOPAZ focused primarily on changes in subroutine PROPS, but changes were also made to other subroutines that read in and define three new directives: ITYP, WIDT, and PERI. ITYP was introduced as a flag for pipe elements that identifies the cross section shape of the pipe. ITYP must be defined by the user for non-circular portions of the venting system, and it is maintained in the array DATA(NEL,46) during program operation. The designations for ITYP are as follows.

- ITYP = 1      serves as the default value and signifies a circular cross section  
 ITYP = 2      signifies a rectangular cross section.

If ITYP is not equal to 1, the user must input an effective diameter that can be used to calculate the correct cross section area when using the equation for a circular area, i.e.

$$Area = \frac{\pi D^2}{4}$$

The user must also input a perimeter, PERI, when ITYP is not equal to 1 such that the hydraulic diameter can be calculated by

$$D_H = \frac{4 * Area}{PERI}$$

This hydraulic diameter is then used in the calculation of parameters such as the Reynolds number, the friction factor, and the Nusselt number for pipes with non-circular cross sections.

WIDT is introduced as the width of a rectangular duct. It must be the largest of the dimensions of the rectangle, and it is used with the area to calculate the ratio of the two sides of the rectangle, i.e.

$$\frac{a}{b} = \frac{Area}{WIDT^2}$$

where  $Area = a*b$  and  $WIDT = b$ . WIDT is maintained in the array DATA(NEL,47).

The following paragraphs describe the revised methodologies that are used by TOPAZ to establish the head loss and heat transfer coefficients for pipes of different cross section shapes with roughness effects included.

## PRESSURE HEAD LOSS

Changes were made to TOPAZ to provide greater flexibility in the calculation of pressure head loss in pipes. The changes focused on head loss that results from fully developed boundary layer skin friction effects. Losses resulting from entrance effects are believed to be incorporated into the loss coefficients for the joint upstream of each pipe entrance.

### Fully Developed Boundary Layer Skin Friction Effects:

The user has the option of specifying the friction factor for pipes with or without entrance effects included. The friction factor is identified in the input data file as FDATA when the flag IF is set equal to 1. If IF is set equal to 2, the friction factor is calculated by TOPAZ. TOPAZ was modified to calculate a laminar friction factor for circular and rectangular duct cross sections when the Reynolds number based on hydraulic diameter is less than 1000.

### Laminar Flow:

For circular cross sections, ITYP=1, the laminar ( $Re < 1000$ ) friction factor is calculated by the function

$$f = \frac{64}{Re}$$

For rectangular cross sections, ITYP = 2, the laminar friction factor is calculated from a curve fit for Figure 6-4 from Ref. [6] as shown in Fig. 1. Here  $f$  is considered to be related to the skin friction coefficient by

$$f = 4 * C_f$$

where  $C_f/Re$  is a function of the rectangular height/width ratio. This height/width ratio is defined in TOPAZ with the parameter

$$\alpha = \frac{Area}{WIDT^2}$$

where WIDT, the duct width, is a required input parameter for pipes with rectangular cross sections. The resulting curve fit in TOPAZ calculates the friction factor for these cross sections with the approximation

$$f = 96/Re(1 - 1.3553\alpha + 1.9467\alpha^2 - 1.7012\alpha^3 + .9564\alpha^4 - .2537\alpha^5).$$

For an infinitely wide slot, this relationship reduces to

$$f = \frac{96}{Re}.$$

### Turbulent Flow:

When the Reynolds number based on hydraulic diameter exceeds 1000, the friction factor is established from the Moody Chart for turbulent flow in pipes [7]. Here, the roughness/pipe-diameter ratio must be input by the user as EPSD, and the value of  $f$  is calculated by the function FMOODY. All cross section shapes can be accurately modeled with the Moody Chart on the basis of the hydraulic diameter, and there is no need to provide alternate methodologies for the various pipe cross sections in turbulent flow conditions.

### HEAT TRANSFER COEFFICIENT

Changes in the methodology used by TOPAZ to model the heat transfer coefficient in pipes include the introduction of non-circular cross section effects, roughness effects, and entrance effects. Previous versions of TOPAZ considered roughness effects on the head loss in pipes, but neglected any roughness effects in heat transfer processes.

### Laminar Flow:

In laminar flow conditions ( $Re < 1000$ ), TOPAZ calculations of the pipe flow Nusselt number were varied for different cross-section shapes. For circular cross sections, ITYP=1, the Nusselt number is established from the theoretical solution for pipe flows with a constant heat transfer rate, i.e.

$$Nu = 4.364.$$

This methodology was used in previous versions of TOPAZ.

For rectangular cross sections, ITYP=2, the Nusselt number is calculated from a curve fit through data points listed in Table 8-2 [6] and presented in Fig. 2 for cases with an assumed constant heat transfer rate. Here  $Nu$  is expressed as a function of the ratio of the hydraulic diameter to the rectangular width and is calculated from the approximation

$$Nu = 4.53(\text{Diameter/Width})^2 - 9.155(\text{Diameter/Width}) + 8.235.$$

### Turbulent Flow:

For turbulent flow conditions TOPAZ first calculates a roughness factor that defines a hydraulically smooth surface using the Moody function with  $EPD = 0.0$ . A turbulent rough wall friction factor is then formulated in accordance with the friction flag directive. When  $IF = 1$ , the friction factor is defined in the input file. When  $IF = 2$ , the fully turbulent rough wall friction factor is defined by

$$f = \frac{-1}{[2 \log(\epsilon/D)]^2}, \text{ where } \epsilon/D = EPD.$$

### Smooth Walls:

When the friction factor for the surface is less than or equal to the smooth wall friction factor, the surface of the pipe is assumed to be hydraulically smooth and the Nusselt number is calculated from the Dittus/Boelter [8] turbulent heat transfer model

$$Nu = 0.023 * Re^{0.8} * Pr^n$$

where  $n = 0.4$  for heating of the flow ( $T_{wall} > T_{flow}$ ), and  
where  $n = 0.3$  for cooling of the flow ( $T_{wall} < T_{flow}$ ).

### Rough Walls:

In cases where the friction factor is greater than the smooth wall friction factor, the Nusselt number is approximated with the empirical [6] Nusselt number ratio

$$\frac{Nu}{Nu_{smooth}} = \left( \frac{f}{f_{smooth}} \right)^{n'}$$

where  $Nu_{smooth} = 0.023 * Re^{0.8} * Pr^n$  and where  $n' = 0.68 * Pr^{0.215}$

The maximum value of the surface roughness ratio  $f/f_{smooth}$  is 4.0 in this approximation.

### ENTRANCE EFFECTS

TOPAZ was modified to include the addition of entrance effects on the heat transfer in circular pipe flows. Here IENT is introduced into the TOPAZ input file as a flag to identify whether entrance effects are to be included for a given pipe element. Its designations are:

- IENT = 0      signifies that no entrance effects are to be considered.
- IENT = 1      signifies that entrance effects will be included.

IENT has a default value of zero, and it is maintained in the array DATA(NEL,48).



The user must specify when entrance effects are to be considered. This is accomplished by designating IENT = 1 for the specific pipes in which entrance effects are to be considered. A running length, RL, is first calculated for each element in these pipes in subroutine PIPE. The running length is measured from the element identified as the upstream element. Future efforts will be made to revise the running length calculation for reverse flow situations.

## HEAT TRANSFER COEFFICIENT

Entrance effects on heat transfer Nusselt number are based upon the data presented in Table 8-12 [6] for flows with a Prandtl number of 0.7, an assumed constant heat transfer rate, and a combined thermal and hydrodynamic entry length. Figure 3 presents these data in graphic form. Here  $Nu$  is expressed as a function of the running length, the Reynolds number based on diameter, and the Prandtl number; i.e.

$$Nu = .0173[\ln x]^{3.6444} + 4.36$$

where  $x = 0.5 * Re * Pr / (X/D)$ , with  $X$  being the running length from the entrance.

## PLANNED MODIFICATIONS

REMTECH plans to make additional modifications to TOPAZ in the future. A coupled surface ablation model to calculate the rate of surface ablation for ablating materials is being considered. This will be used in part to calculate changes in the wall surface areas during the ablation process. For walls which possess different surface materials in regions along its perimeter, changes will be made to allow for the input of individual surface material thermal properties. This will allow TOPAZ to directly calculate the effective thermal properties for the surface. REMTECH also plans to investigate the possibility of accommodating temperature dependent thermal properties.

## REFERENCES

- [1] Winters, W. S., "TOPAZ — The Transient One-Dimensional Pipe Flow Analyzer: User's Manual," SAND 85-8215, Sandia National Laboratories, Livermore, CA, Jan. 1983.
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- [6] Kays, W. M. and Crawford, M. E., *Convective Heat and Mass Transfer*, McGraw-Hill Book Company, New York, 1980.
- [7] Moody, L. F., "Friction Factors for Pipe Flow," *ASME Trans.*, Vol. 55, 1944, pp. 671-684
- [8] Dittus, F. W. and Boelter, L. M. K., *Univ. of California Pub. Eng.*, Vol. 2, 1930, p. 443.

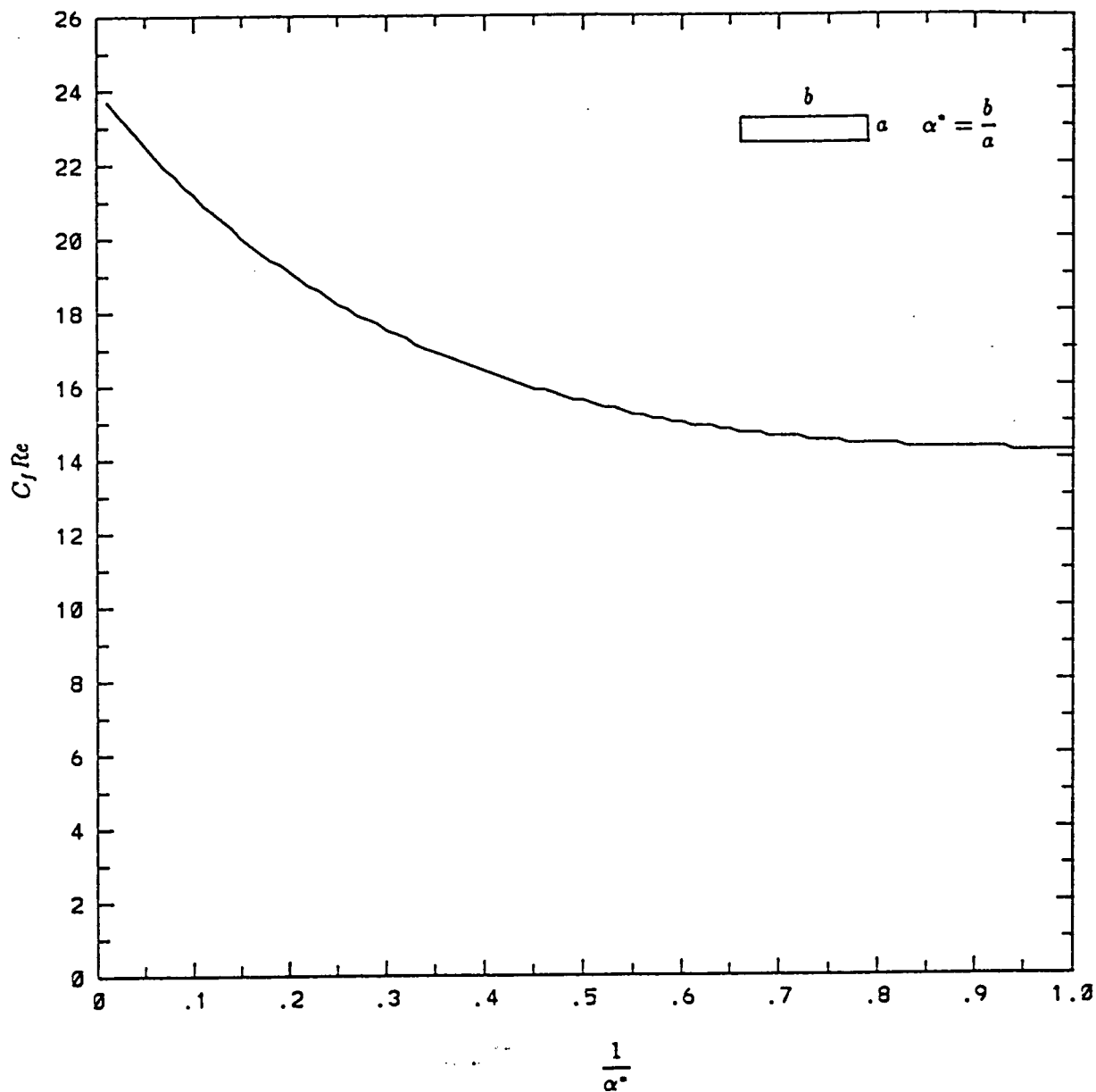


Figure 1: Friction Coefficients for Fully Developed Laminar Boundary Layers in Rectangular Tubes [6]

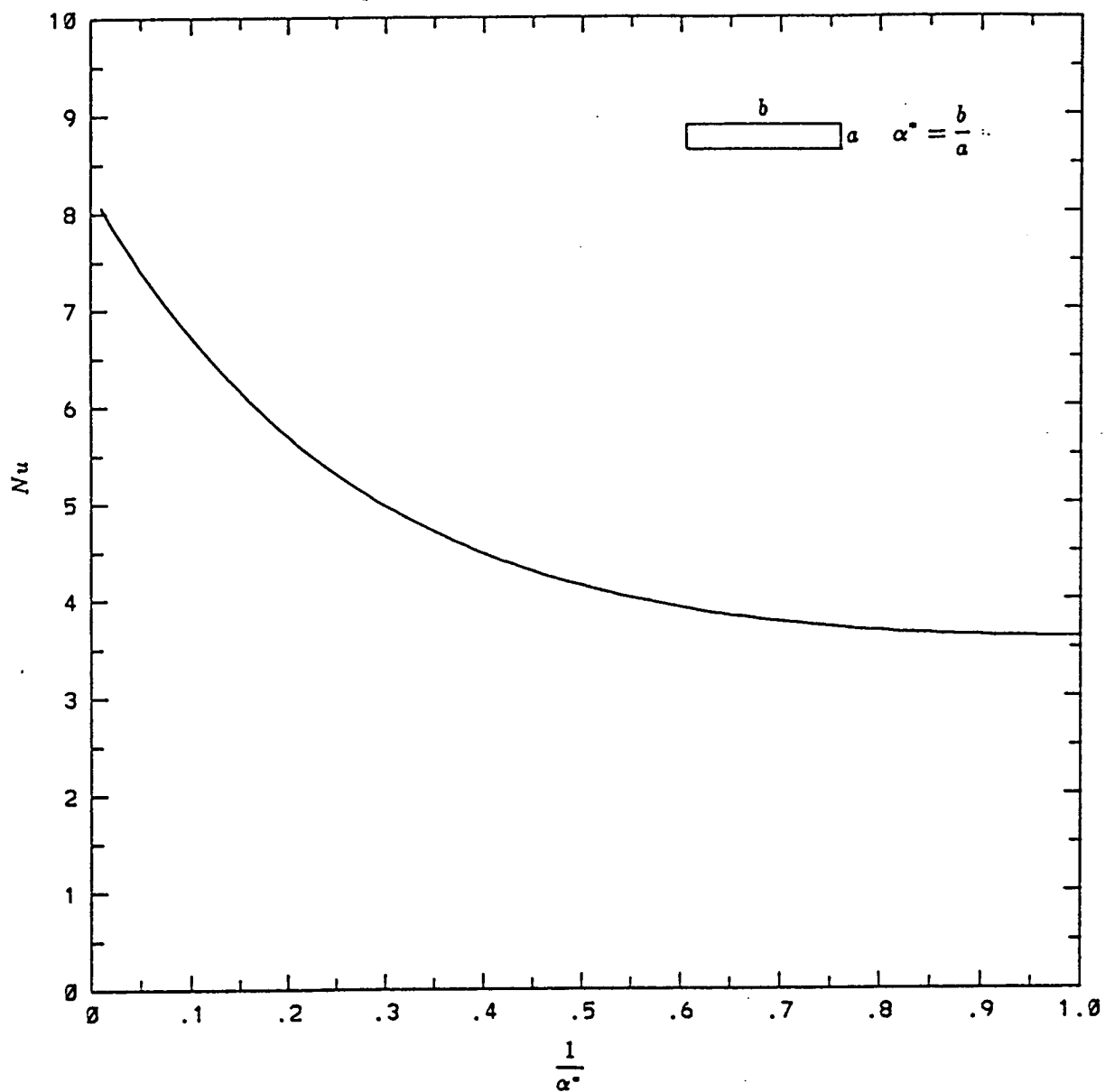


Figure 2: Nusselt Numbers for Fully Developed Laminar Boundary Layers in Rectangular Tubes [6]

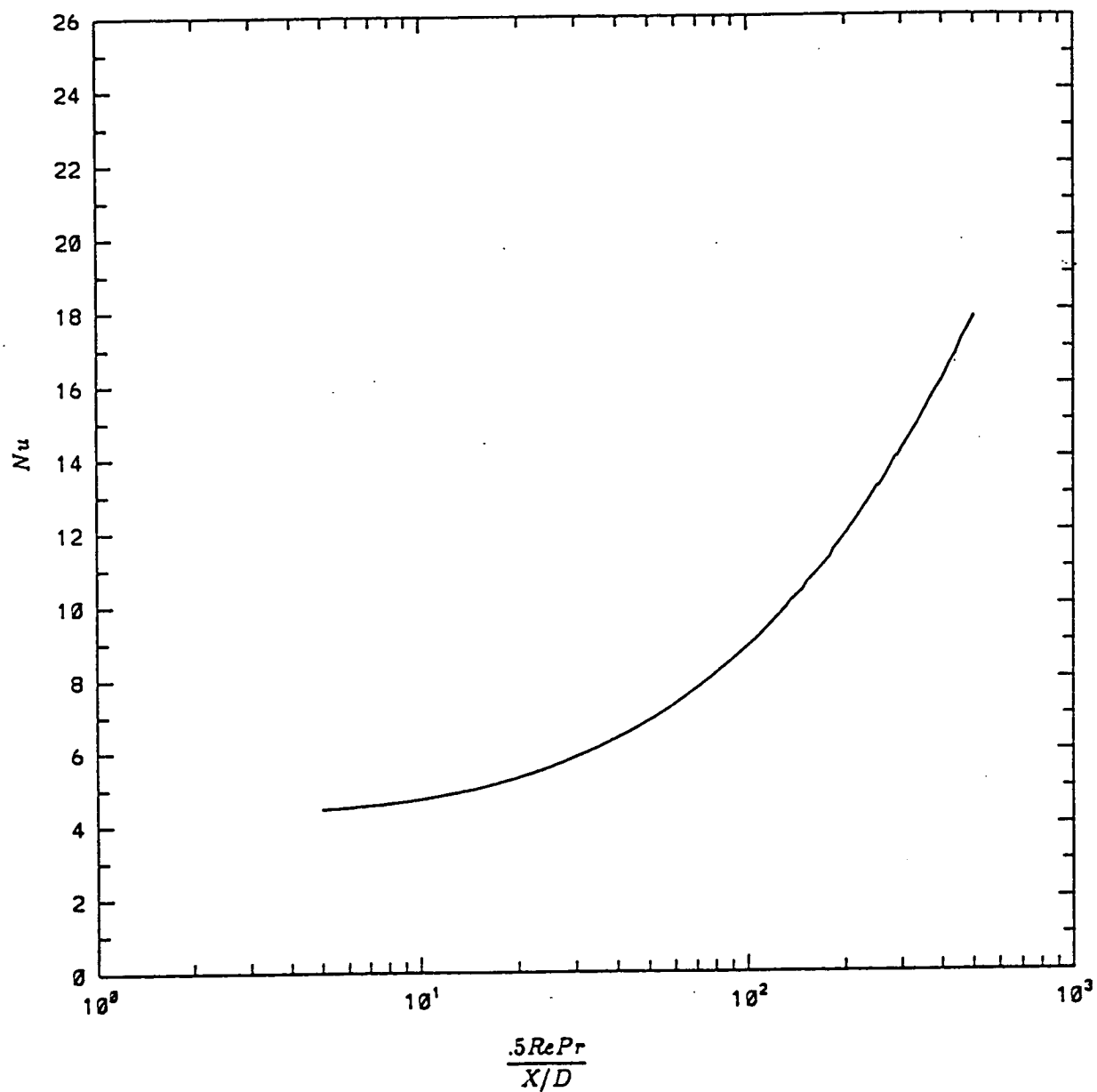


Figure 3: Nusselt Numbers for Laminar Flow in Entry Length of a Circular Tube [6]